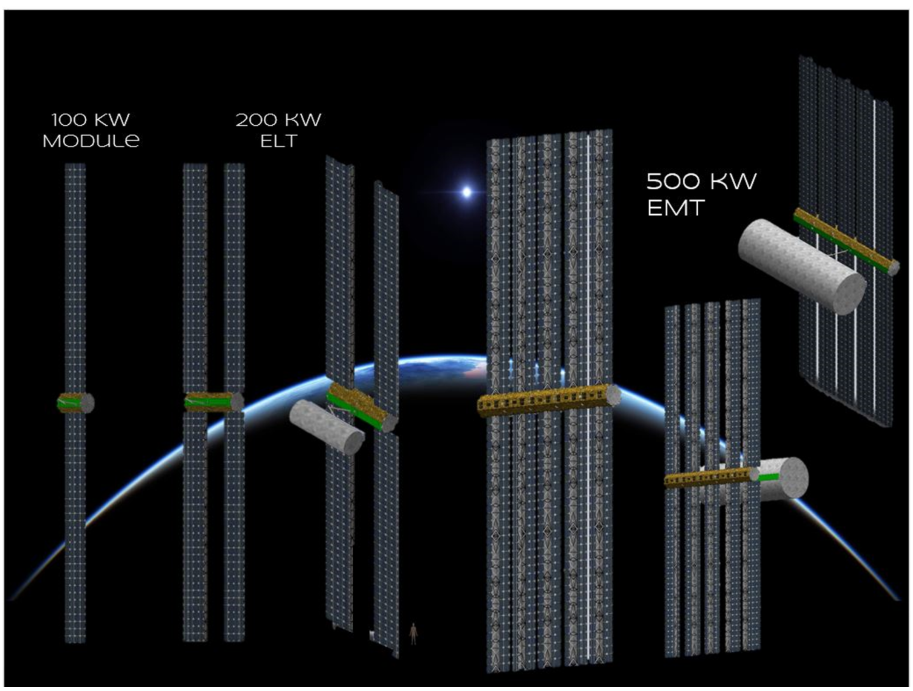
Odysseus: A Proposed Solar-Electric Propelled Tug for the 2016 BIG Idea Challenge

Justin Norman[*], Olivia Zanoni[†], Gabriel Walker[‡]
Brian Sanders [§]
University of Colorado at Boulder
Colorado Space Grant Consortium

In 1919 in his paper A Method of Reaching Extreme Altitudes, Dr. Robert H. Goddard suggested how one may travel to the moon, an answer to what is a very difficult engineering challenge.[8] Regular recurring travel to the moon is an even more demanding task, requiring a specific type of craft emphasizing reusability and maintainability. This paper describes one possible design of a modular 200 kilowatt(kW) solar electrically propelled (SEP) tug composed of two smaller 100kW modules for the transfer of cargo and vehicles from low Earth orbit (LEO) to lunar distant retrograde orbit (LDRO) with the ability to be expanded to 5 modules for a 500kW interplanetary SEP tug. Each individual module will have each of its subsystems compartmentalized providing the ability to replace faulty subsystems without the need to replace the entire module/spacecraft.



*Department of Aerospace Engineering Sciences, CU Boulder
†Department of Physics and Engineering Physics, CU Boulder
‡Department of Aerospace Engineering Sciences, CU Boulder
§Deputy Director, Colorado Space Grant Consortium

I. Introduction

The thought of traveling to the moon and into the solar system beyond on a regular basis is one that has been present in mankind's collective consciousness since at least the creation of science fiction. The moon is considered the first stepping stone to the rest of the solar system, and rightfully so, as it is the nearest of the celestial bodies at a "paltry" 384,400 kilometers on average. However, regular travel to the moon is no easy task. Such a craft must be reusable with a long lifetime, ideally with no more maintenance than refueling in orbit. It is a challenge with no previous formal address outside of the theoretical. The 2016 Breakthrough, Innovative and Game-changing (BIG) Idea challenge seeks to elicit possible solutions to this problem.

There are several obvious traits any solution must have: an efficient propulsion system requiring very little fuel; a high degree of autonomy; and, of course, the ability to travel to and from lunar orbit. Clearly, it would be most efficient for the craft to use ion propulsion, and the craft should be modular for reusability and longevity purposes. The craft's efficiency could be further heightened for example by assembling it in orbit from smaller component craft.

Odysseus is one possible solution to the BIG Idea challenge. It builds the solar tug out of smaller independent modules to form a single tug. The base 200 kW of electric thrust is divided between two 100 kW modules each with a thruster bank made of five clustered Hall effect thrusters, and the other subsystems are distributed similarly. Because of this, each module can be individually tested on the ground to ease the assembly process similar to the construction of the ISS This design represents the highest levels of mission architecture necessary to convey the most pertinent ideas for successfully meeting the design requirements. The design as a whole is best described as a conglomerate of effectively tested and implemented space technologies, drawing on the collective successes of robotics, ion propulsion, solar deployment, autonomous operation, and many more to create a spacecraft that has the potential to enable significant human lunar and Martian presence.

II. Definition of Terms

MODULE Also 'tug module'; a 100 kW self-contained spacecraft able to physically connect with others like it to form spacecraft of a higher power class than that of a single 100 kW craft

ELT Earth Lunar Transport; the 200 kW spacecraft; composed of two 100 kW self-contained spacecraft (modules); the spacecraft for lunar travel

EMT Earth Martian Transport; A 500 kW class spacecraft composed of five 100 kw spacecraft (modules)

BRACE Berthing and Rendezvous Arm Control Environment: Robotic arm manipulator and its multiphase operation environment

III. Mission Overview

A. Requirements

To be accepted, each proposal to the BIG Idea Challenge must meet 5 hard requirements and take into account an additional 8 design factors. The hard requirements are as follows:

- Complete assembly of the tug should take no more than 60 days.
- The tug's solar array must provide at least 200kW of power to its engines nominally and at the end of life; this is in addition to any power needed by the other subsystems.
- The structural components of the tug must withstand up to 0.4 g's of acceleration on orbit.
- The fundamental flexible body vibration mode should be at least 0.05 Hz or higher. This is of particular importance for large deployable solar panels.
- The tug must be designed such that the underlying components can be scaled up to build a 500kW SEP tug for deep space missions.

There are several design factors that must be kept in mind and expressed in the final concept; these are:

- Design simplicity – In general, since simpler designs have fewer points of failure, the lower the risk of using that design is, which in turn leads to a higher probability of mission success. Also practically speaking, since this proposal comes before the prototyping and testing phase, each aspect of the tug's design should be as simple as possible to reduce confusion, misinterpretation and to provide an elegant solution to the problems faced.
- Low system mass âĂŞ– Not only does this reduce cost, but it also increases the number of different launch vehicles that can be used.
- Ground testability of the assembly process –âĂŞ Since robotic assembly and permanent berthing of unmanned spacecraft has never been done before, proving that the method of assembly can be tested here on Earth will be one of the keys to the proof of concept.
- System level modularity –âĂŞ The ability to replace or add subsystems means that in the case of a failure of one or two subsystems, the entire spacecraft is not lost and can be easily repaired.
- Packaging for the least number of launches âĂŞ– Since multiple rockets are expensive, only needing a few rocket launches is more cost effective.
- Concept of operations for robotic assembly and module deployment –âĂŞ Proof that additional thought has been put into the specifics of the assembly process.
- Ability to remove and replace modules –âĂŞ Similar to system level modularity.

IV. System CONOPS

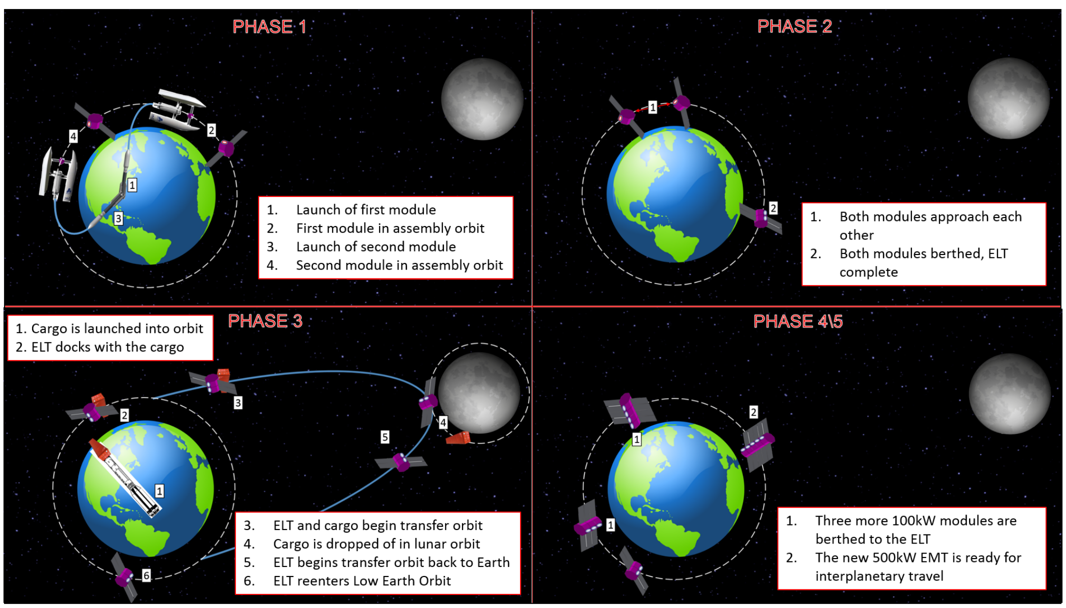


Figure 1: Diagram of CONOPS

By relegating each module to 100 kW each, the ELT would then require two launches before it is ready to transport up to 10,000 kg of cargo. The concept of operations consists of four main phases, starting by executing the two launches required to get both modules into Low Earth Orbit (LEO), then moving into the assembly and module deployment phase, followed by the main cargo transport phase, and finishing with the tug service phase.

A. PHASE 1 - Launch

The mission will begin by launching the first module of the ELT aboard a Falcon 9 rocket into equatorial prograde LEO from Kennedy Space Center, separating from the launch vehicle upon arrival into orbit. Once the first module is in orbit, the next module will launch into orbit from the Kennedy Space Center (KSC) for rendezvous with the first module. The launch vehicle is responsible for precision insertion of the second module such that the respective trajectories and relative velocities fall within a tolerance. The final module approach, defined by the last stage separation will mark the end of the launch phase.

B. PHASE 2 - Assembly and Module Deployment

Once the second module has executed its final stage separation and resides in the target rendezvous orbit, its propulsion system and Reaction Control System (RCS) will be responsible for translation. The target orbit must be slightly lower in altitude than the first, allowing the second module to use the slightly higher velocity inherent in the lower orbit to slowly catch up to the second module. This difference in orbit altitude must be low enough to keep the relative velocity of the respective modules below a tolerance, but large enough to allow for a timely assembly process. The objective is to optimize the second modules orbit such that the RCS system is responsible for as little ΔV as possible, which greatly reduces the risk associated with assembly the assembly phase. The most delicate and computationally intensive part of the mission with regards to the ADCS will arise from the need to process precise attitude and trajectory information from both modules simultaneously in order to autonomously align the respective modules with each other to initiate the assembly berthing sequence. Once both modules are aligned and in close formation proximity, the robotic arm will deploy and begin honing in on the other module. Its grapple fixture will for latch onto the other module and physically bring the two respective docking ports together for a successful berthing sequence. Once the arm has completed its tasks, Phase 2 is terminated. This phase will take much less than the originally expected 60 days as the precise orbital trajectory combined with a chemical based RCS system puts the spacecraft in a highly controllable ADCS environment.

C. PHASE 3 - Cargo Phase

Once the SEP Tug is fully assembled and comfortably in LEO, its primary cargo phase will begin, entailing a readiness for rendezvous with an inbound cargo module. A similar berthing sequence to the assembly phase will ensue with regards to the coupling of the tug and cargo, utilizing the tug system robotic arm to attach itself to the cargo module. Once successfully coupled, the Ion propulsion system will begin its continual prograde burn, marking the start of its traverse across cislunar space. The solar panels will utilize their range of motion actuation to maintain maximum exposure across the majority of the journey. Upon Lunar Distant Retrograde Orbit (LDRO) arrival, the robotic arm will appropriately release the cargo and begin its journey back to LEO for the next cargo module.

D. PHASE 4 - Service Phase

The fuel capacity of the tug will be enough to satisfy the thrust requirements for 2-3 round trips to the moon and back. Once a refuel procedure is necessitated, a designated refuel service module must be employed to bring the tug its additional xenon. The Orbital Express mission and it's successful completion of autonomous robotic refuel and replacement has given this phase sufficient validity for the purposes of Odysseus. Using a berthing procedure similar to the assembly phase, the cargo rendezvous phase, and the process demonstrated by Orbital Express, successful xenon mass transfer can be accomplished with relatively low risk.

E. PHASE 5 - Repurpose

The lifetime of the SEP Tug is expected to be around 10 years. Over this time it will make at least 5 round trips between LEO and LDRO, combining and separating with several cargo modules for lunar transport. Once the main mission transport phase is considered complete, the re-purpose phase will begin and will involve the following scenario. The SEP Tug will simply require an additional three modules to reach 500 kW status to become power ready for an interplanetary transfer. This series of berthing sequences would be similar to the launch and assembly phase of the 200 kW version, and take place in LEO.

V. System Replacement CONOPS

Subsystem replacement is not a matter of fully removing the subsystem from the rest of the system. Instead, it is a matter of reconfigurability and redundancy to keep on orbit replacement simple. Each module is flown with a few hard-wired additional subsystems kept down from power. Should a subsystem need replacement, the commanding processor will cut power to the damaged subsystem and bring its pre-existing replacement up to power.

VI. Subsystem Analysis

A. Structural

The primary geometric form of each tug module resembles that of an extruded octagon. Since it is more structurally sound to have the cargo attach to the tug in line with the engines and since at least two solar arrays would be needed per module, each module would need to have at least 4 sides. In order to make the best use of the cylindrical volume of the payload section of the Falcon9 while keeping a large face area to fold the solar panels upon, an octagonal shape was chosen for the modules. Each sector of the cross sectional octagon has been allotted a specific subsystem as seen in figure 3. This design allows for system level modularity and reusability, while also reducing cost and design complexity. Additionally, since each module is the same spacecraft, the launch of a single module is all that is required to prove that this design is viable. This will greatly lower manufacturing costs since the 500kW tug and/or additional only require more of the same modules to be made as opposed to multiple different crafts.

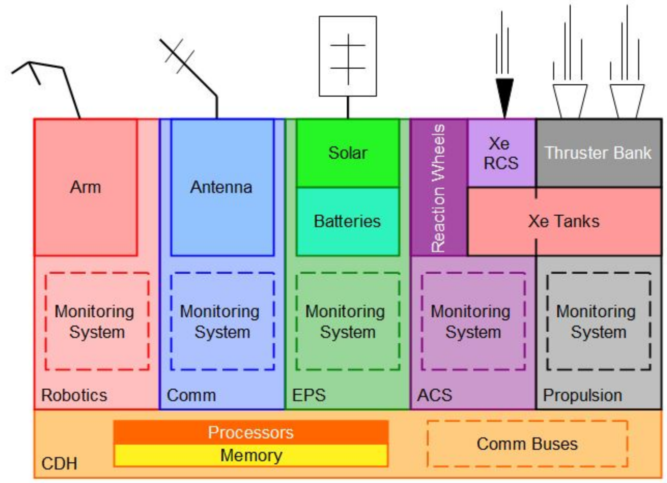


Figure 2: Module System-Level Functional Block Diagram

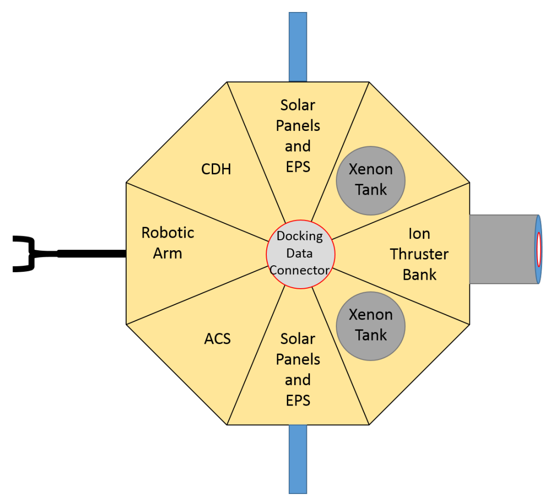
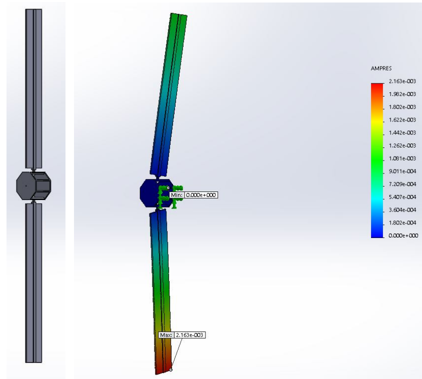


Figure 3: Subsystem Distribution Within Each Module

The subsystem sector construct allows for their even distribution in the tug as a whole. For example, with regards to propulsion, smaller Ion thrusters can be linked in series to proportion the thrust to mass ratio for accommodation of any number of tug modules. This design also allows for the complete individuality of each module, which is essential for the assembly process, as each module must be able to behave as its own spacecraft by having a full and functional subsystem suite. Each module will have standard autonomous docking ports on the large face sides to allow a series of modules to be physically and electronically linked to form the overall tug. It is important to note that any number of tug modules may be used to accomplish the same task, just at different scales. In order to meet the requirement that the flexible body vibration mode be 0.05 Hz or higher, the SolidWorks frequency analysis tool was used to perform a vibrational analysis on a single module with itâĂŹs solar arrays in two separate configurations. The first configuration is with the solar arrays pointing straight up and down (straight configuration) to simulate when the module is pointing straight at the sun. The second configuration is when the solar arrays are slid to the sides of the solar array boom (offset configuration) to simulate when the module is pointing perpendicular to the sun and the solar arrays are fanned out. In the straight configuration, the lowest vibration mode is at 0.23 Hz with a max amplitude of 0.07 m occurring at .23 Hz. In the offset configuration, the lowest vibration mode is at 0.20 Hz with a max amplitude of 0.06 m also occurring at 0.20 Hz.

It should be noted that due to the constraints of the program used, the module had to be modeled as a solid object as apposed to having individual components. To get the values stated above, the module was composed of 6061 Aluminum Alloy. A secondary analysis was performed to verify that the structure can withstand a structural load of at least 0.4g's. The simulation that was developed calculated maximum stresses at approximately 2kPa, located at the hinges connecting the module with the solar panels. This simulation ran at a force input of 5.1g's.



(a) Solar wing no stress (b) Solar wing with stress

Figure 4: Solar Panel Configuration Stress Analysis

B. EPS

Since the tug is expected to operate for at least 10 years and needs to produce 200 kW of power, the only practical option for generating electricity is to use solar panels. The power budget was estimated and can be seen in Table 1. Based off of currently existing space grade solar panel efficiencies of 30.7%,[19] the solar panel area needed to power the tug can easily be calculated using the equations on page 412 of Space Mission Analysis and Design (SMAD).[10]

Approximately 692 m^2 of solar panels would be needed for each 100kW module. Since the solar cells themselves are only about a quarter of a millimeter thick, only minimal structural support is needed and two designs were considered. The first design uses a deployable boom with the solar panels folded up in front of the boom similar to the solar panels on the ISS and MMA's R-HaWK solar array. This design has the benefit of not producing any torques when deployed, but since all the solar cells will be folded on top of each other they will be more susceptible to vibrating into each other during launch. The second design integrates the support structure and the solar cells into multiple plates that are folded together similar to the solar panels on the Juno spacecraft. This design has the benefit of fewer folds and thus less solar cell to solar cell contact, but requires some sort of spring or motor at each joint to deploy the array and it also produces a torque when deployed. Due to it's mechanical simplicity, proven design and low mass, the boom deployment method was the one that was chosen. This design also allows the solar panels to be recessed into the body of the module when stowed as opposed to lying on the outside face of the module. Using MMA's calculation that every 4 folds of the solar array is 3.31 cm tall, and since each solar array will need to be folded 29 times, each solar array of each module will fold up into a volume of 6.7 X 1.66 X 0.24 m.

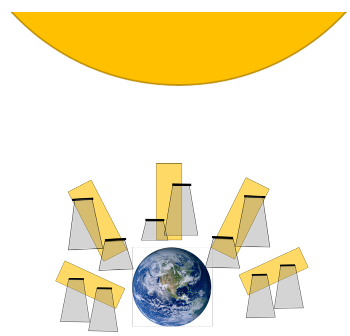


Figure 5: Solar Panel Movement at Various Points in Orbit (yellow is the ELT, black is the solar panels and gray is the shadows cast by each solar array)

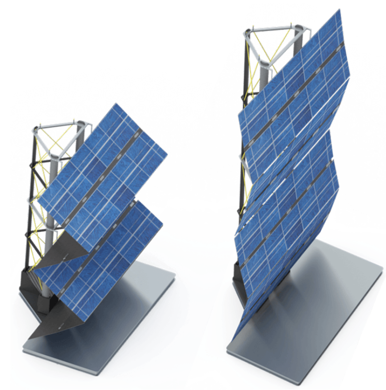
To assist in power production, the panels will be mounted on a swivel joint to enable each array to always face normal to the sun. Additionally, to mitigate the fact that the the solar arrays will cast a shadow on each other at various points in the orbit each solar panel will be able to slide side to side with relation to the solar array boom and ELT.

C. ADCS

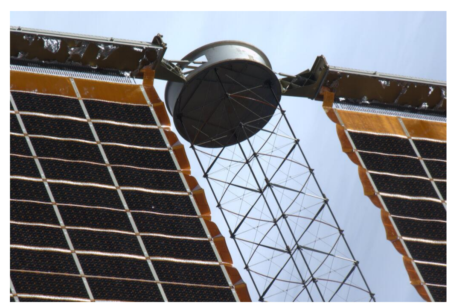
Table 1: Power Budget

	Estimated Power Consumption (W)
CDH processor unit	200
Reaction wheels	200
Robotics	10
Solar array movement	200
Comm	50
Sensor suite	50
Thermal heat pumps	100
Propulsion	100,000
Total	100,450

The ADCS system will be distributed evenly across the modules to help compensate for the change in center of gravity after assembly. The ADCS system will be comprised of standard reaction control wheels, a cold-gas xenon-based reaction control system, and the primary thruster bank. As the thruster bank is built of five separate thrusters, the direction of the thrust vector can be finely controlled. This allows the craft to use the thruster bank as a means of attitude and reaction control. The thruster bank will also be used to slough off the majority of the craft's angular momentum through thrust vectoring in addition to the momentum dispersion efforts of . This will keep the rest of the ADCS system from becoming saturated during the craft's ten year lifetime.



(a) MMA's R-HaWK Solar Array



(b) Solar wing with stress

Figure 6: Solar Panel Configuration Stress Analysis

RCS

To accelerate quickly and avoid collisions, the tug modules must carry an RCS system. Clearly, given the long lifetime of the tug, this system cannot be a traditional chemically-based system. Using ion thrusters for the purposes of an RCS would also be ineffective, as it would not allow for the craft to accelerate quickly enough. The only viable RCS type is thus cold-gas. The most logical cold-gas propellant is the xenon gas already onboard for the thruster bank.

Cold-gas reaction control is nothing new; the SPHERES robots and AERCam both use pressurized neutral gas as a reaction control system. Using xenon as the propellent is something more 'exotic'; however,in 2014 a Japanese research team designed, built, and tested a xenon RCS system for a small satellite,[9] and in the early 2000's, NASA's own Johnson Space Center designed MiniAERCam, a follow-up to the cold-gas propelled Autonomous Extravehicular Activity Robotic Camera Sprint, to navigate with cold xenon reaction control.[13]

D. Communications

Because of the modular interchangeable nature of the tug, a highly directional antenna would be problematic to implement without having specialized modules dedicated to this task. However, after some initial research and consultation[1] it was discovered that an omnidirectional antenna would have sufficient transmission capabilities to maintain contact up to and when in lunar orbit.[1] Additionally, with some clever designing each individual module can include an antenna that when connected to other modules forms a larger dipole antenna for the entire tug. The DSN is a completely viable network for the this missions multiple communications purposes. Budgeting roughly 10 Watts of power to the antenna, the DSN has open bands in the 2200 MHz and 8500 MHz range at 63 dBi and 75 dBi gains, respectively. Relatively low data rates in the kilo-bits range can be expected. After several consultations with RF space communication specialists, it was determined that an omnidirectional antenna at 10 Watts on the DSN will be more than sufficient for successful communications at lunar distances.

The interplanetary class tug will have to have a slightly modified communication subsystem since no currently existing omnidirectional antenna can transmit a signal from such distances at such low power. One possible solution is attaching a directional antenna to one of the two ends of the tug to support this missiorn phase.

E. CDH

As the tug is to be autonomous, the CDH system must be quite robust. CDH must be able to handle subsystem replacement and formation flying, just to name two points of interest. The most interesting aspect of the CDH subsystem is how each module will communicate with the others in a coherent manner. Before docking, each module is independent, and after docking, one processor will become the primary processor in the system, and the other will become the secondary processor. If a scenario requires it, the secondary has the ability to become the primary in the system, thus increasing redundancy and reliability.

Control Structure

The control structure of the tug requires special consideration, given the natural redundancy of having two physically identical processing units onboard. For simplicity, the two will work together in a primary-secondary relationship. The choice of which of the two processing units acts as primary in the system is arbitrary.

The secondary is 'hot' and has the additional responsibility of checking and watching the primary to help limit the effects of radiation on the control structure. In the event of primary failure, the secondary will assume the role of the primary.

As an example of control flow-down, top-level system logic flow is given for the docking sequence in figure 7.

```
while dockingSensor reads notDocked:
    readSensors:
        star sensor
        gyro
        magnetometer
        accelerometer
        proximity sensor
        partner orientation sensor
        docking
    if dockingSensor reads docked:
        break
    decideWhatToDo:
        -Accelerate toward partner
        -Decelerate w/ respect to partner
        -Rotate about axis
        -Docking
    doIt:
        -Firing engine(s)
        -Use reaction wheels/RCS
        -Docking
    continue
```

Figure 7: Docking Sequence Logic Flow-down

Sensors

Each module's sensor suite must include a star sensor, an accelerometer, a gyroscope, a magnetometer, a docking sensor, a partner orientation sensor, and internal electronic system monitors to provide the control structure enough information to make decisions autonomously.

F. Propulsion

Because of the long lifetime (10+ years) and nearly continuous activity (at least 5 round trips to LDRO), most traditional propulsion methods were deemed impractical. Though chemical rocket engines have the highest thrust to weight ratio (up to 100 g's[10]) of almost any propulsion method, their low Isp means that they require large volumes of fuel and would need to be refueled more often than would be practical. Since long term viability and autonomy are more important factors than orbital transfer time, only propulsion methods with higher Isp values are considered. The remaining propulsion methods to be considered then are nuclear fusion, passive (no internal reaction mass), and electromagnetic. The lack of a full scale demonstration automatically eliminates the first two choices, leaving only electromagnetic propulsion.

Because of their high efficiency frequently approaching 60%, Hall effect thrusters are the obvious choice of the electromagnetic propulsion types.[2] As the tug will be composed of two largely-independent modules, there is a need for 100 kW of Hall effect thrust for each module. Few monolithic thrusters with the required power rating exist, although choosing a monolithic thruster for this purpose is not viable in any event: testing a 100 kW monolithic thruster would be difficult, and for attitude control and angular momentum control, there must be a fine degree of control over the direction of the thrust vector. Clearly then a cluster of Hall effect thrusters must be used instead.

Clustering Hall effect thrusters has been a subject of research for at least the past ten years, and many institutions have dedicated much time and effort to it. This research, particularly that by the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory, has given rise to several interesting results that must be taken into consideration during the design of a Hall thruster cluster; for instance: the total thrust and specific impulse of a cluster is greater than the simple summation of the thrust and impulse of the component thrusters (believed to be a result of a focusing effect of the thrusters' plasma plumes on each other); an accelerating electric potential from a reversed electric field exists in the gaps between thrusters (believed to be a result from the overlap of individual thrusters' plasma plumes); and when operated with a shared power source, the supply power circuit must be carefully designed to ensure proper current balancing (results indicate component thrusters tend to draw current unevenly in a basic circuit).[2] For simplicity's purposes, the total thrust and specific impulse of the thruster cluster will be calculated with the simple summation of the thrust and specific impulse of the component thrusters, and it will be assumed each component thruster is dispersing the same amount of power.

To reach the necessary 100 kW of propulsive power for each module craft, it was decided to build a cluster of five 20 kW Hall effect thrusters. The 20 kW thruster used for calculation purposes is the PPS-20kW ML built by French researchers S. Zurbach, N. Cornu, and P. Lasgorceix as part of the European Space Agency's High Power Electric propulsion: a Roadmap for the Future (HiPER) project. HiPER was meant to investigate high power electric propulsion systems, and some of its results—including those of Zurbach, Cornu, and LagorceixâĂŤ– were presented in 2011 at an international conference on electric propulsion. This particular thruster was selected for its specifications and the extensive testing it underwent. A cluster of five PPS-20kW ML thrusters has a total thrust of 5000 milliNewtons (mN) and a specific impulse of 12000 seconds (s) when operated at 400 Volts (V) per thruster. The cluster can also be operated at 500 V per thruster; the thrust is then 5250 mN with a specific impulse of 13500 s. The total dispersed power per thruster at 400 V is measured 19.3 kW and is measured 22.4 kW at 500 V; the designers state the relationships between discharge voltage and thrust and specific impulse are nearly linear. As such, a power of 20 kW per thruster is reached at a discharge voltage of 450 V, which gives the cluster of five thrusters a total thrust of 5100 mN and a specific impulse of 12500 s.[23] This particular thruster was chosen for ease at this stage of design, as it underwent extensive testing and has its specifications provided.

Propellant Requirements

A single PPS-20kW ML thruster consumes 42 milligrams (mg) of xenon gas per second when dispersing 20kW of power, so a cluster of five thrusters consumes 210 mg of xenon per second.[23] Using the numeric method described in the later orbital mechanics section, the time of burn was found for three values of the total mass (cargo and ELT) of the ELT. These mass values were determined with methods described in the later mass estimation section. This, of course, provides a way to calculate the mass of xenon gas consumed while burning out to lunar distance:

Table 2: Xe Mass and Time of Burn vs. Xe Mass

Total Mass (kg)	Time of Burn of One Orbit Transfer (s)	Mass of Xe for Single Module (kg)
12,000	5,967,000	1253.07
15,000	7,450,000	1564.50
16,500	8,165,000	1714.65

Naturally, for a single trip from LEO to LRDO and back, each module would have to carry over double these masses of xenon for return travel, orbital insertion, and RCS purposes.

To find the volume required to contain such a large mass of xenon gas, the authors examined the experimental results from the design and construction of a xenon tank for use in space.[21] This particular tank was tested successfully to hold the xenon gas at a certain pressure and temperature, and this pressure and temperature was used for volumetric calculations. Given its high density, xenon must be modeled with the van der Waals equation, and this gave a volume of 994.5 L for a single trip to lunar distance. A single wedge of the octagonal extrusion was calculated to have a volume of 12 m^2, more than enough for xenon storage even with carrying enough to return to LEO, insert into orbit, maintain the RCS, and providing space for electrical and structural components.

G. Thermal

Standard thermal analysis of heat transfer rates via radiation are sufficient in determining the design surface area of the spacecraft's thermal radiators. To help keep internal temperatures at acceptable tolerances throughout the radiation environment that the spacecraft will experience, two radiators must be used to encompass the full solar exposure inherent in the orbital path. Each radiator will be located on the surface of opposite octagonal sectors of each tug module, such that the radiation being emitted by them does not interfere with the attached cargo. The heat input of each tug module is primarily generated by the ion drives, each producing about 8.2 kW of heat. The CAD thermal analysis shows temperatures around 300 degrees C, which is extremely high, but still a number with a high degree of uncertainty associated with it at this point in the design.

Granted, there are extreme thermal circumstances being encountered between the heat supplied from the clustered ion drive and the sun on the large amount of solar panel surface area, but radiating that heat shouldn't be too significant of a problem, although very large radiators will be needed. Initial estimates for radiator surface area are around 10 square meters, but should reduce as the design develops more, especially with considerations like potential use of thermoelectric generation from the solar panels via a new technology currently being developed at McDonald, Dettwiler and Associates (MDA).[5]

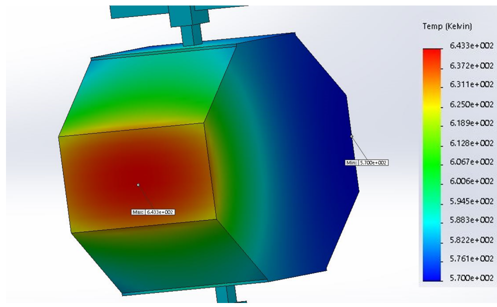
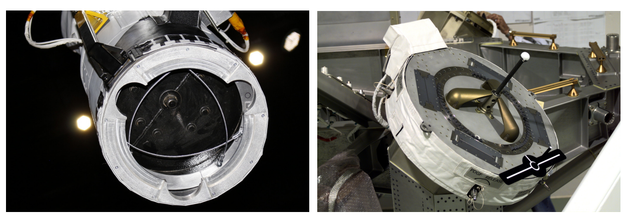


Figure 8: Thruster contributions to temperature profile

Figure 8 illustrates a rough idea of what the heat distribution will look like, with regards to the thruster input. Solar heat sources and internal electrical heat sources will add to this model. Heat sources at each solar panel base will be channeled with the other heat sources towards the radiators hexagonal face via active heat pipes.

H. BRACE Robotics and Cargo Tug

Quintessential to the success of the mission is the utilization of a robotic arm manipulator similar to the ones implemented on the ISS, Space Shuttle, and Orbital Express missions. The Berthing and Rendezvous Arm Control Environment, BRACE, will be responsible for assembling the tug, attaching to the cargo module, and assisting the service module for refueling. Once the navigation system has gotten the tug to within an acceptable distance of the target, a mechanical arm will deploy to secure the two objects together, be they cargo modules, service modules, or other tug modules. The robotic arm is physically located on the opposite side of the main thrusters. It is to be constructed in a way that allows it to fold up into and deploy from its octagonal sector. It's grapple fixture will be almost exactly the same as the ones utilized in previous missions, as depicted in Figure 9, with an additional power transfer capability for potential cargo requirements. (a) depicts the arm manipulator and the cables it uses to tighten around the grapple shaft in (b). Canadarm was used as an illustrative example as its grapple fixture is almost identical to the ones desired on Odysseus.



(a) Arm (b) Grapple Point

Figure 9: Grapple Fixture of Canadarm

BRACE requires the dexterity to perform berthing procedures under almost the exact same circumstances as those outlined by their implementation in the aforementioned missions. Using cameras and specialized control software for actuation the grapple fixture hones in on the contact point, tightening the cables illustrated in Figure 9a around a grapple shaft in Figure 9b to secure the two objects. The grapple fixture then rigidizes itself and performs whatever subsequent task is required by the mission phase.

I. Docking

In order to enable the spacecraft's CDH subsystem to easily integrate multiple tug modules together, an electrical connection is necessary in the dock latching mechanism to allow for communication between each module. A scaled up version of the universal docking port developed for the NASA SPHERES satellite with an electrical connection would act as an excellent mechanism for successful tug assembly.[20]

VII. System Analysis

A. Mass Estimation

Determining the mass estimations associated with Odysseus involved analyzing subsystem mass ratios from other similar missions. With the expected 10,000 kg mass of cargo, and the known 1,300 kg mass of solar panel, the only thing left was to estimate the mass of the physical tug module. This was done by estimating the mass ratio of the solar panels to the total tug mass to be about 0.5, meaning the tug module itself should be about twice the mass of the solar panels. With this in mind, the total mass of the spacecraft was estimated to be 15,000 kg. This mass consists of the xenon tanks, the xenon propellant, aluminum structure, the solar panels, and the electrical components. The lower mass estimate of the spacecraft is 12,000 kg and the upper mass of the spacecraft is 16,500 kg. The reason for a larger upper mass uncertainty is due to the variability in mass that the solar panels may have. Future improved simulations in force and frequency may change the mass estimations.

Table 3: Mass Distribution

	Mass (kg)
Propellant	3,200
Solar Panels	1,300
Cargo	10,000
Additional Components	500
Total Mass	15,000

B. Orbital Analysis

As the spacecraft uses such a low-power propulsion system, all orbital maneuvers must be undertaken with a non-instantaneous "burn". The finite burn problem is a difficult one, and indeed no analytical solution exists. When not describing a change in orbital inclination or orientation, the problem is described by a system of seven coupled non-linear differential equations provided by Curtis.[4]

This system is solved by numerically integrating over the duration of the burn. To do so, the authors wrote a script in Python, and the results were plotted. The results can be seen below:

Interestingly, the system behaves as a weakly-forced harmonic oscillator, so the craft takes a spiraling path out to lunar distance. The system is highly sensitive to the initial mass of the craft, and so to gain an increased understanding of the system, the time of burn for three different masses were found. These values can be seen in the table below:

Table 4: Burn Times vs. Mass

Total Mass (kg)	Time of Burn (s)	Time of Burn (day)
12,000	5,967,000	69.0
15,000	7,450,000	86.2
16,500	8,165,000	94.5

These values were calculated assuming a total thrust of 10.2 Newtons with a starting circular orbit with a radius of 8378 kilometers and further assuming the thrust vector remains tangent to the orbit at all times.

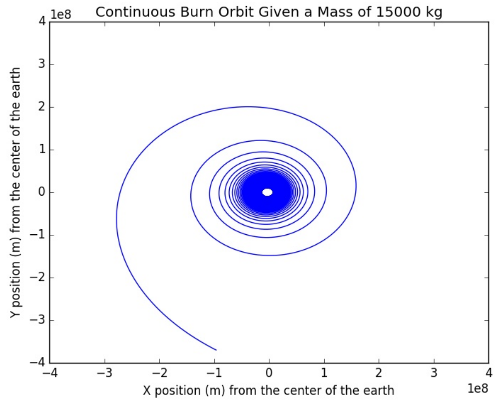


Figure 10: Orbital trajectory from LEO to LDRO

C. Tug Assembly

The assembly process relies primarily on autonomous berthing. For a 200 kW tug, two separate 100 kW modules are required. This involves a single orbital rendezvous and berthing procedure. Using the xenon RCS system and reaction wheels for translation and attitude control, it is possible to very finely tune the attitude and relative velocity of the respective modules. Several missions that demonstrated technologies directly applicable to assembly purposes were researched for validity's sake. DARPA conducted a highly applicable orbital berthing demonstration called Orbital Express that drastically reduces the risk associated with such a process. Their use of robotic arms and autonomous operation to berth two spacecraft in LEO is proof of concept that this method is highly efficient and reliable. The Italian Space Agency conducted a series of relevant missions called PRISMA, which provide proof of concept that precise, close proximity, autonomous control of multiple spacecraft in orbit is not only feasible, but entirely reliable for the assembly purposes of the SEP tug mission.[7]

D. Upper-Level Modularity

Great emphasis was put into the modularity of the spacecraft design. As mentioned above, the tug consists of a series of modules, each capable of independent autonomy and operation. Each module is designed to integrate and enhance other modules into a fully operational tug system by effectively distributing all module subsystems. When needed, the subsystems can be replaced by a simple procedure.

The ability to control very complex movements of multiple spacecraft in orbit is tricky, but reliable given robust enough control algorithms. Thus, a removal and replacement maneuver involving ejecting the affected module and repeating the assembly process would suffice to successfully replace any given module. The worst case replacement and removal scenario involves an affected module in the middle of the 500 kW tug, which entails first decoupling the tug as a whole into stable formation at the affected module. A rotation of the portion containing the affected module must then be performed to aim away from the other tug portion before the affected module is jettisoned. Once the old module has been distanced sufficiently and the new is on approach, the tug portions will configure themselves for a sequential assembly process involving attaching the new module to where the old one was, then reattaching the two remaining tug portions back together.

E. System-Level Modularity

Each module carries extra electronic hardware for EPS, ADCS, and monitoring systems, and CDH and structure are inherently modular by the rest of system design.

F. Radiation Environment

While traveling to and from LRDO, the tug will pass through the Van Allen radiation belts. This requires special attention, as this will expose the tug to high levels of radiation. CDH will have to implement watchdogs and will have to be shielded from this intense environment to protect it from the adverse effects of radiation.

G. Testing

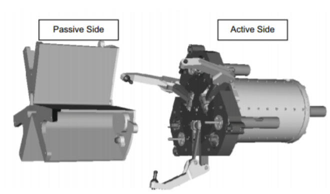
In order to ensure effective ground testability of the assembly process, simplicity in the module docking procedure was prioritized in the tug design. By reducing the assembly process to a single docking sequence for the 200 kW tug version, ground tests can easily be constructed to verify the assembly feasibility. Neutral buoyancy tanks are an effective way to simulate the environments being encountered during the post-rendezvous assembly process. With two separate tug modules present within a neutral buoyancy tank, it would be possible to undergo experimental tests to analyze the attitude determination and control subsystems and how effectively they utilize the reaction control system in successfully coupling with one another. Another prospective testing technique involves using a potential predecessor of the SSDT (Small Satellite Dynamics Testbed) that JPL's GNC teams use to simulate attitude control tests for multiple Cubesats simultaneously. If a scaled versions of the SEP tug design were replicated for testing with something like JPL's SSDT, very accurate results would ensue due to the nature of the low thrust long duration assembly process.

H. Lifetime

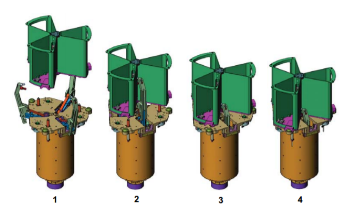
The tug must have a minimum lifetime of 10 years. Given a time of 86 days of travel time as found by the finite burn calculations to lunar orbit and an assumed 30 days of time spent in either low Earth or lunar distant orbit before changing orbit, the tug can make just less than 2 full round-trips from LEO to LDRO to LEO or from LDRO to LEO to LDRO in one year, or, alternatively put, 15 full round-trips in 10 years.

I. Servicing

Each module of the completed tug will have the ability to be refueled and serviced once back in LEO. This further extends the lifetime of the tug and lowers degradation. The service module will require an additional launch sometime before the first refuel is needed. It will be parked in LEO with stores of xenon in readiness for rendezvous with Odysseus upon its return from the moon. The service module will also utilize technology involved with DARPA's Orbital Express mission, in particular it's refueling capabilities. The docking port used aboard Orbital Express is capable of reliable xenon fuel transfer, and can extend the lifetime of the ELT and EMT tug versions by years. A service module allows for the servicing of multiple tug craft simultaneously, and requires little complexity.



(a) Docking system mechanism



(b) Capture Sequence

Figure 11: Orbital Express grappling concept

VIII. Launch

Two standard Falcon 9 launches are required to get the 200 kW SEP tug into LEO, each carrying its own module.

A. Packaging

Since the core of each module is 4.6 m X 6.7 m, each module will be able to fit nicely inside of the 4.6 m X 6.7 m payload section of the Falcon 9's fairing as seen in figure 12. The only component that will need to be in a special state for launch are the solar panels which will be folded up inside of each module. These can then be deployed once separation from the fairing is complete.

B. Launch Vehicle

Three main factors were looked at to determine which launch vehicle(s) to use: cost, reliability and the maximum mass it can carry to LEO. We chose to use Space X's Falcon 9 rocket to carry each module into orbit because not only does it have a high success rate (>90%), but its reusable first stage greatly lowers the cost of each flight. The Falcon 9 also has the ability to carry up to 21,000 kg into LEO which allows a lot of flexibility when designing the tug. An added benefit to using the Falcon 9 is that it is manufactured right here in the United States. A total of 2 Falcon 9 launches will be needed to construct the ELT with any cargo and/or service modules requiring their own launch(es).

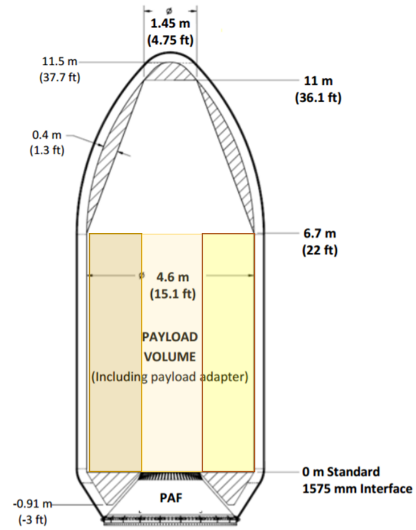


Figure 12: Module inside of the Falcon9 Fairing

IX. Discussion of Design

A. Feasibility

Relying on the CDH subsystem and sensor arrays for ADCS during the assembly and cargo docking portions of the mission is a highly reliable way of successfully executing these tasks. After discussing the process in detail with satellite navigation expert, Professor Hanspeter Schaub, it was determined that the nature of an ion based RCS would be ideal in precisely controlling the spacecraft's movement in feedback loops performed by CDH. The launch vehicle should be able to deliver the modules to within a close enough range such that the low thrust from the ion propulsion would be able to dock them within the 60 day assembly period.

The area of this mission associated with the highest uncertainty is the performance of the mechanical tug arm and its ability to reliably couple with cargo modules. While the precision of the tug movement is very high, the mechanical arm design must take into account these movement constraints and the risks associated with them, as well as maintaining the ability to deploy and retract in and out of the spacecraft.

Only one piece of experimental technology are used in this design: the PPS-20kW ML Hall effect thruster. However, the PPS-20kW is not the only thruster in its power class and was selected purely for convenience at this stage of the design, as it underwent extensive testing and its specifications can be easily found.

On the whole, several pieces of the proposed mission have not been done before, but they are also built upon well-developed science. It is entirely possible to answer the demands of each of these pieces together, even if doing so is not an easy task.

B. Requirement Satisfaction

Complete assembly of the tug should take much less than 60 days. Since the ELT will be comprised of 2 modules and since each will likely weigh approximately 13,500 kg, the worst case scenario (each module needs) a separate launch, then the launch to dock time of each module will take the full 60 days, but average assembly time will most likely be quicker. Therefore, this requirement is met.

The tug's solar array must provide at least 200kW of power to its engines by the end of life; this is in addition to any power needed by the other subsystems. Using the assumptions and calculations listed in equations (1) through (4), the entire tug will need approximately 230kW at the beginning of life to provide 215kW to the entire craft with a dedicated 200kW for the engines after 10 years of use. Using the design listed in the EPS section above, this requirement is met.

All structural components of the tug must withstand up to 0.4 g's of acceleration, and the fundamental flexible body vibration mode should be at least 0.05 Hz or higher. Structural analysis preformed using the tools of SolidWorks shows the structure does not displace to the point of critical damage and has a body vibration mode of 0.20/0.23 Hz.

Finally, the tug must be designed such that the underlying components can be scaled up to build a 500kW SEP tug for deep space missions. Since the 200kW tug will be entirely composed of smaller homogeneous 50kW modules, construction of a 500kW tug will be as simple as berthing 5 modules together. The main issue would be the tug's antenna since a modular omnidirectional antenna is not practical for deep space missions. This however is addressed in more detail along with some proposed solutions under the CDH section. Hence this requirement is met as well.

C. Technology Readiness Level Summary

Of the 11 main technologies used in this design, the lowest technology readiness level (TRL) is level 6 (System/subsystem model or prototype demonstration in a relevant environment). Of the 11 technologies, the Solar cells, tug servicing, heat pipes, CDH partnership and robotic servicing all have a TRL or 9 having been flight proven through successful mission operations. Since both close formation flying and continuous burn orbits have each only been done once (in the manner that Odysseus will use them), they have a TRL of 8. Finally, since the solar deployment, Hall thruster clustering, 20 kW Hall thruster and xenon RCS have all been tested in a relevant environment but not in space, they are given a TRL of 6.

X. Conclusion

In astronomical terms, the distance to the moon is nothing. In engineering terms, it is a significant hurdle. Nevertheless, regular lunar travel can only widen the open door to spacefaring. It is a challenge that must and will be tackled, and surprisingly, most of the required science and technology has existed for a decade or more.

Odysseus is one solution to this multi-part problem and takes the concept of modularity to one of its extremes. It proposes building the solar tug out of smaller independent spacecraft able to dock together and function as a single craft. The base 200 kW of electric thrust is divided between two 100 kW craft each with a thruster bank made of five clustered 20 kW Hall effect thrusters, and the other subsystems are distributed similarly. The key components of each subsystem are also separated inside each module such that they can be easily changed without needing to pull the whole module apart.

Figure 13: Technology Readiness Levels of each technology used

Assuming certain conditions about launch, orbit, and spacecraft maneuvering, it would take 60 days for the tug to assemble in Low Earth Orbit, and assuming continuous thrust always tangent to the orbit, it would take 59 days for the tug to travel from Low Earth Orbit to Lunar Distant Orbit. Given 10 days in each orbit before orbit change, the tug would be able to complete 20 full round-trips LEO-LEO in ten years.

On the whole, Odysseus is a flexible, feasible solution meant to simplify the problem of modular construction in several ways, and it has several important consequences and implications. Chiefly among them is the natural scalability; by changing the power of the modules, any amount of power in the final craft can be obtained with any number of modules. As such, an Odysseus craft can be tailor built for any mission, and this is Odysseus's greatest strength by far.

In a few years, mankind will be wandering the solar system, and a critical part of that effort will be reusable long-lived spacecraft. Perhaps we will find these craft are built of smaller craft.

References

[1]Apollo 9 Press Kit. (2000). N.p.: National Aeronautics and Space Administration News.

[2]Beal, B. E. (2004). Clustering of Hall effect thrusters for high-power electric propulsion applications. Doctoral dissertation, University of Michigan, Ann Arbor.

[3]Canadarm (2015, April 23). In Canadian Space Agency. Retrieved January 20, 2017, from $http : //www.asc - csa.gc.ca/eng/canadarm/default.asp$

[4]Curtis, H. D. (2010). Orbital Mechanics for Engineering Students (Second ed.). Burlington, MA: Butterworth-Heinemann.

[5]Dougherty, Sean. MacDonald, Dettwiler and Associates Ltd. Personal interview. 25 Jan. 2017.

[6]Electrical Power System (2000, August 31). In Kennedy Space Center. Retrieved from http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-eps.html

[7]ESA. "PRISMA (Prototype) - EoPortal Directory - Satellite Missions." PRISMA (Prototype) - EoPortal Directory - Satellite Missions. Swedish Space Corporation, 2016. Web. 21 Nov. 2016.
https://directory.eoportal.org/web/eoportal/satellite-missions/p/prisma-prototype

[8]Goddard, R. H. (1919). A method for reaching extreme altitudes. Smithsonian Miscellaneous Collections, 71(2).

[9]Koizumi, H., Inagaki, T., Kasagi, Y., Naoi, T., Hayashi, T., Funase, R., and Komurasaki, K. (2014). Unified Propulsion System to Explore Near-Earth Asteroids by a 50 kg Spacecraft. 28th Annual AIAA/USU Conference on Small Satellites.

[10]Larson, Wiley J.(2005). USpace Mission Analysis and Design (Third Ed.). Microcosm Pressl, 412.

[11]Lohmeyer, Whitney Q.(2015, March 19). Space Radiation Environment Impacts on High Power Amplifiers and Solar Cells On-board Geostationary Communications Satellites.
http://ssl.mit.edu/files/website/theses/PhD-2015-LohmeyerWhitney.pdf

[12]McDonald, Dettwiler and Associates. Retrieved January 15, 2017, from $http : //mdacorporation.com/$

[13]NASA Johnson Space Center's Miniature Autonomous Extravehicular Robotic Camera (Mini AERCam) (2002, February 24). In Johnson Space Center. Retrieved January 28, 2017.

[14]Orbital express space operations architecture (n.d.). In Defense Advanced Research Projects Agency Tactical Technology Office. Retrieved from http://archive.darpa.mil/orbitalexpress/index.html

[15]RRM - Robotic Refueling Mission (n.d.). In Goddard Flight Center Satellite Servicing Projects Division. Retrieved January 28, 2017, from $https : //sspd.gsfc.nasa.gov/robotic_refueling_mission.html$

[16]Sandford, Stephen. Stinger Ghaffarian Technologies. Personal interview. 27 Jan. 2017.

[17]Schaub, Hanspeter. Colorado Center for Astrodynamics Research, University of Colorado Boulder, Department of Aerospace Engineering Sciences. Personal interview. 23 Nov. 2016.

[18]Shoemaker, Kevin. Shoemaker Labs. Personal interview. 10 Jan. 2017.

[19]SPACE Solar Cells (n.d.). Spectrolab. Retrieved December 11, 2016, from http://www.spectrolab.com/solarcells.htm

[20]SPHERES Home. Massachusetts Institute of Technology, 2014. Web. 30 Nov. 2016.
http://ssl.mit.edu/spheres/

[21]Tam, W. H., Ballinger, I. A., Kou, J., Lay, W. D., McCleskey, S. F., Morales, P., & Taylor, Z. R. (1996, July 1). Design and Manufacture of a Composite Overwrapped Xenon Conical Pressure Vessel. 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference.

[22]Vela, Jannine. MMA Design LLC. Personal interview. 2 Feb. 2017.

[23]Zurbach, S., Cornu, N., & Lasgorceix, P. (2011). Performance Evaluation of a 20 kW Hall Effect Thruster. The 32nd International Electric Propulsion Conference, Wiesbaden, Germany. Doi: IEPC-2011-020