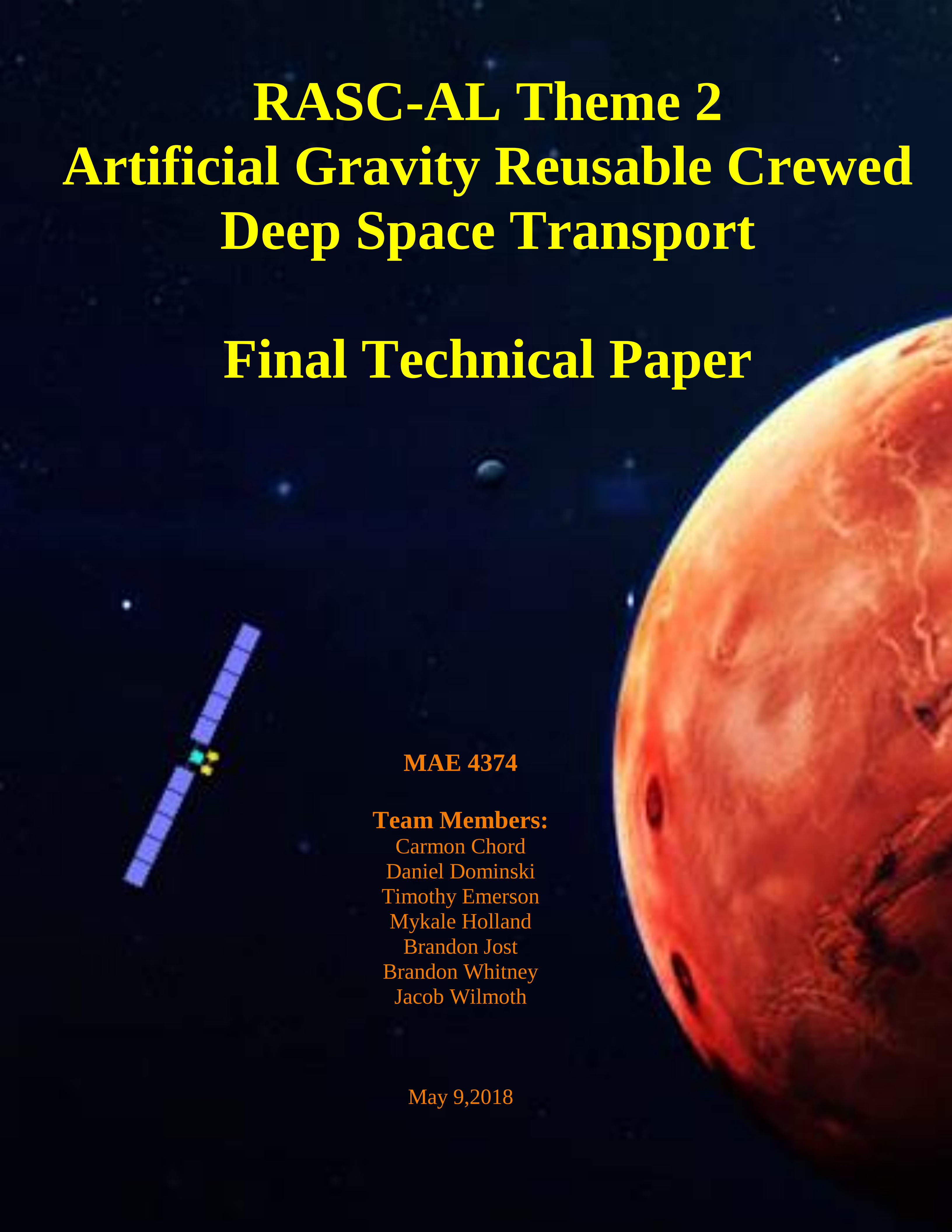

RASC-AL Theme 2
Artificial Gravity Reusable Crewed Deep Space Transport

Final Technical Paper

MAE 4374

Team Members:
Carmon Chord
Daniel Dominski
Timothy Emerson
Mykale Holland
Brandon Jost
Brandon Whitney
Jacob Wilmoth

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1.0 Introduction

As part of the quest for humankind to reach Mars, the problem of astronaut health on extended space voyages must be addressed. The team at Oklahoma State University aims to solve one major element of that challenge – extended micro-gravity exposure. As outlined in RASCAL Theme 2, there is a need to create artificial gravity in a reusable crewed deep space transport for the manned missions to Mars. In response to this challenge, the team at Oklahoma State University proposes Project Daedalus. The goal of Project Daedalus is to create a spacecraft system that is capable of simulating a Mars level gravity during a majority of the mission to Mars through the use of centripetal force. Project Daedalus will utilize a baseline habitat and a storage pod counterweight connected via a shaft that will rotate around a central hub attached to the propulsion system. This rotation will simulate the necessary gravity needed for astronaut health and comfort during the mission.

1.1 Mission Overview

There will be a minimum of three roundtrip missions to Mars with each beginning in cis-lunar orbit and travelling a 5-sol Martian orbit which will take roughly 300 days to achieve. Once in Martian orbit the astronauts will travel to the surface and stay for an extended period of time to conduct experiments. At the end of the surface mission, the crew will return to the waiting spacecraft and make another 300-day journey back to Earth.

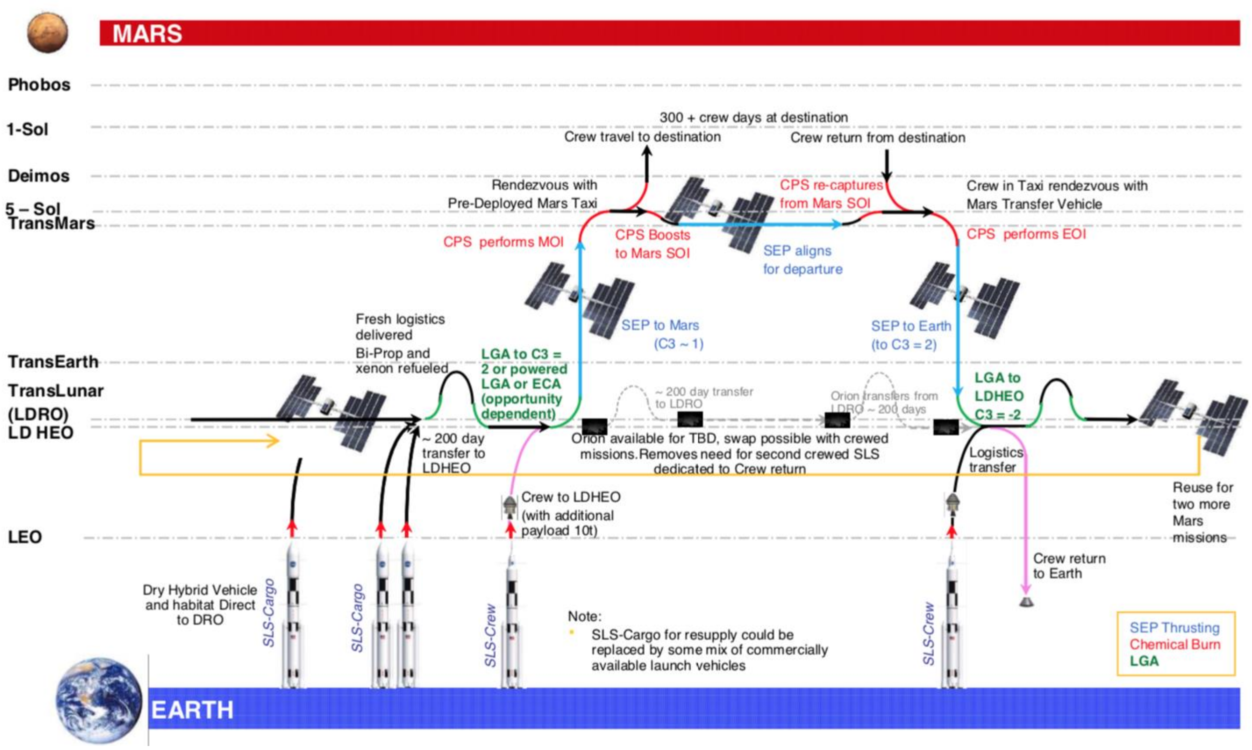

Figure 1 – Mission Concept of Operations (CONOPS)[1]

[1] Chai, Patrick. "Mars Hybrid Propulsion System Trajectory Analysis Part I: Crew Missions."

2.0 Proposed Design

The Mars mission will be launched from cis-lunar orbit using the propulsion system described in RASC-AL Theme 1 which is capable of transporting approximately 50 metric tons for the duration of the conjunction class round-trip Mars mission. The spacecraft will launch from cis-lunar orbit in a hammerhead configuration, Figure 2, until the transition from the high-thrust chemical system to the low-thrust electric system has been completed. Once this transition has been completed, it will transform into the transit configuration, Figure 3. The transit configuration will enable the necessary rotation to produce the artificial gravity. In order to transform into this transit configuration, expandable shafts will be necessary to push the pods apart from the central hub to the desired length of 84.6-meters.

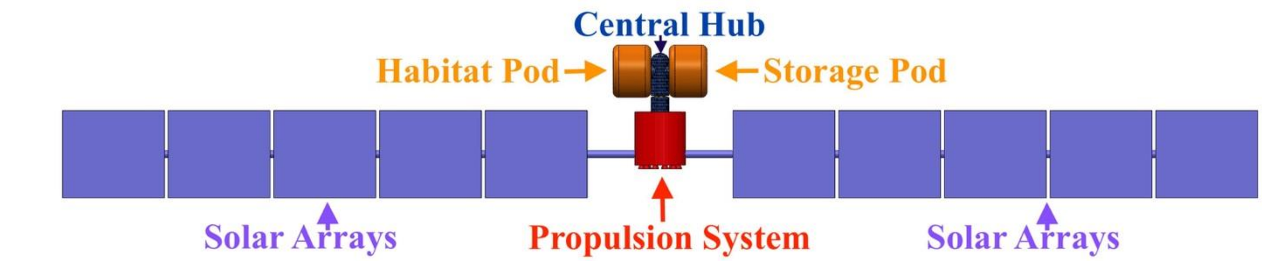

Figure 2 - Hammerhead Configuration

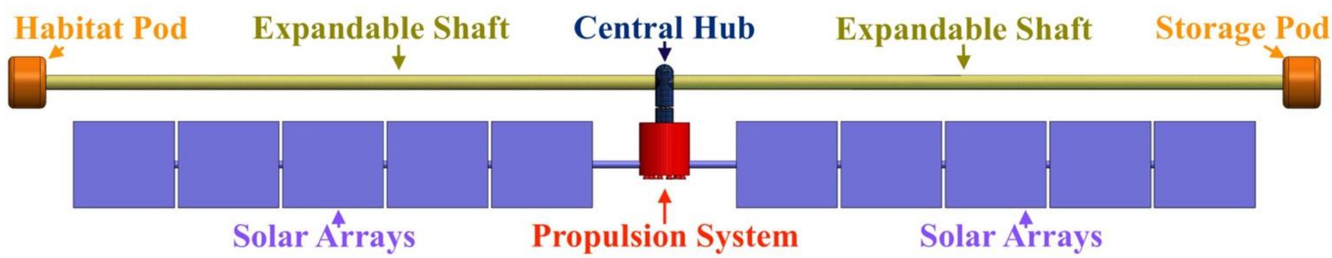

Figure 3 – Transit Configuration

The central hub will decouple pod rotation from the propulsion system and allow normal deployment of the solar panels. Once the shafts are fully expanded, thrusters on each pod will be used to rotate the system to the desired 2 RPM. Not only will the support booms need to be capable of withstanding the rotational loads, they will also need to tolerate the loads that are exerted on them from the electric propulsion system and vehicle re-orientation. After the rotation reaches the desired speed, momentum will then keep the system rotating at this speed until the spacecraft nears Martian orbit. Prior to the chemical burn to achieve a Mars orbit, thrusters will be used to slow the rotation back to a stationary position relative to the propulsion system. The transit orientation process will be reversed to bring the pods back to the hammerhead configuration for the Mars orbital insertion. Once the astronauts have completed their mission on Mars, the return journey of the mission will follow the same protocol to arrive back to cis-lunar orbit.

2.1 Central Hub

The baseline habitat and storage pod system will be connected to the propulsion system by a central hub that will allow the habitat/pod system to rotate while keeping the propulsion system from spinning. If the propulsion system were to spin with the habitat/pod system, the solar panels would no longer be properly aligned with the sun which would impact the amount of thrust generated by the electric system. To help prevent the propulsion system from rotating, a bearing assembly, and torque cancelling motor inside the central hub will need to be used in the interface between the propulsion system and the central hub. The propulsion system and central hub will need to be affixed to one another after being launched from Earth. This can be achieved by using large bolts that permanently join the two together. A more complex docking system was also considered like the ones used on the International Space Station (ISS), but those would add mass to the system and be unnecessarily complex. The central hub extends out 8.1 meters from the propulsion system to avoid any interference between the solar panels and the pod system. The current configuration has 2.18-meters clearance between the pods and the solar arrays. The solar panels have also been resized from NASA's baseline so that each panel is 14-meters long by 12-meters tall with a total of 10 panels. This configuration of solar arrays maintains the same total area as NASA's baseline but allows for a more compact overall configuration. The central hub to propulsion system stand-off can be increased if further dynamic analysis shows a need for more clearance.

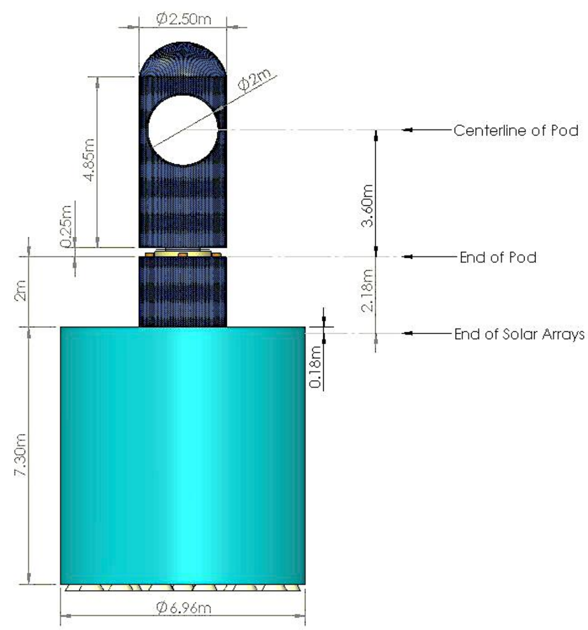

Figure 4 - Central Hub Dimensions

The central hub will need to withstand the loads of chemical thrust, electric thrust, and rotation which means that a strong material must be used. It also must be lightweight since the propulsion system has a 50-metric ton limit so aluminum, Ketron PEEK, and Cetex PEEK were chosen to be investigated further. Table 1 shows the comparison between these three materials. Cetex PEEK was chosen since it has much higher tensile and compressive strength while remaining extremely light.[4] It also performs well in the extreme temperatures of a space environment. JAXA has performed a three-year study on the effects of radiation on PEEK plastics which showed that the effective strength of the material only has minimal degradation when exposed to radiation.[2] Based on the loads during chemical thrust, which is 890-N, the central hub will need to use Cetex PEEK sheets that are 1.175 millimeters thick.[3]

	Ketron PEEK[4]	Aluminum[5]	Cetex PEEK[6]
Mass	Light	Moderate	Light
Tensile Strength (MPa)	75.84	310	2,400
Compressive Strength (MPa)	137.9	207	1,300
Thermal Properties	Excellent in extreme temperatures	Good at cold temperatures	Excellent in extreme temperatures
Technological Readiness Level	TRL 8	TRL 9	TRL 9

Table 1 – Central Hub Material Trade Study

2.1.1 Bearing Assembly

It is the bearing assembly that allows the propulsion system to remain static while the pod system rotates. Preliminary analysis showed magnetic bearings and roller bearings as viable options for the bearing assembly. Neodymium magnetic bearings were chosen because roller bearings may require maintenance several times during the mission due to outgassing lubricant. Also, the magnetic bearings near-zero friction allows for a smaller torque cancelling motor. The only technical issue with magnetic bearings is the possibility of magnetism degradation due to radiation exposure. Research on the effects of radiation with the magnetism of neodymium magnets have shown that at 280 Mrads or higher, the highest degradation seen is 10%.[7] During the mission to Mars, the expected radiation doses would be much lower than 280 Mrads, but in the event that this occurs the magnetic bearings should still remain powerful enough to function properly.[8] The bearing assembly will use passive magnets that are 1.15 meters in diameter with a height of 0.5 meters that surround an aluminum 6061 shaft that has an outer diameter of 1.5 meters, 3.175 millimeters thickness, and 0.5 meters length.[9] There will be two sets of neodymium magnets that will repel each other to create the levitation force necessary to allow rotation about the stationary shaft.[10] In order to prevent the bearing assembly from sliding off of the shaft during thrust changes, spacers and slip rings will be used to limit the assembly's sliding motion. Locking mechanisms will be included to secure the system when not in rotation mode.

[2] Nakamura, Takashi, "The Space Exposure Experiment of PEEK Sheets Under Tensile Stress"
[3] See RASCAL Central Hub Dimensions Calculations PDF
[4] Baer, Scott. "Ketron HPV (Extruded & Compression-Molded) Bearing Grade PEEK Specifications."
[5] "6061 Aluminum Round."
[6] "TenCate Cetex® TC1220."
[7] Alderman, J. "Radiation-Induced Demagnetization of Nd-Fe-B Permanent Magnets."
[8] Dunbar, Brian. "Space Faring: The Radiation Challenge Unit."
[9] See RASCAL Magnetic Bearing Dimension Calculations PDF
[10] Kondoleon, Anthony. "Magnetic Bearings at Draper Labratory."

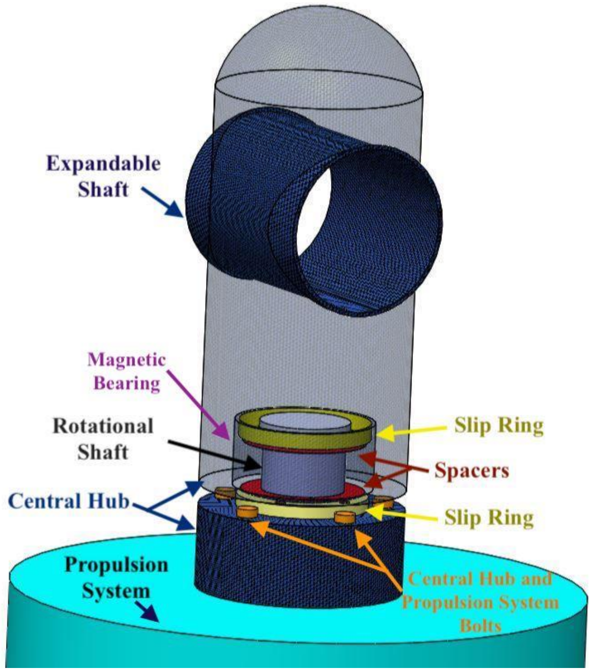

Figure 5 – Bearing Assembly

	Magnetic[11]	Roller[12]
Material	Neodymium Magnetic	Steel
Friction	No	Yes
Lubrication	No	Yes
Possible Issue	Magnetism degradation	Parts wear down due to friction
Maintenance During Mission	No	Possibly
Technological Readiness Level	TRL 9	TRL 9

Table 2 – Bearing Trade Study

A rotary connector will go through the bearing assembly to transfer power from the propulsion system to the pod system. This will allow for the power and data transmission lines to run through the rotating portion of the spacecraft without causing the wires to twist. The rotary connector will connect to a main bus switch which will then connect to a DC converter unit and finally to a remote power controller before going on to power the necessary equipment. This method is very similar to the how power is distributed on the ISS. The representative rotary connector used for this design is the Mercotac Model 1500 which is capable of transferring a maximum amperage of 500 amps and can run a variety of voltages.[13] The baseline model does not meet all of Project Daedalus' power requirements, such as the power required for the spin-up thrusters. This can be remedied with a custom rotary connector that is designed specifically for this mission. As NASA has not finalized the equipment that will be sent on the Mars' missions, the power numbers used in the power calculations are educated assumptions. It is assumed that 100 kilowatts would be sufficient to power all necessary systems on board with the exception of

[11] Kondoleon, Anthony S. "Magnetic Bearings at Draper Laboratory", *NASA Technical Server*
[12] Hamrock, Bernard J., "Rolling-Element Bearings", *NASA Technical Server,* June 1983
[13] "Mercotac Rotary Connection."

the rotational thrusters which would require 204 kilowatts for spin-up. Another assumption that the power distribution in the propulsion system could provide a high voltage source of power, around 500 volts, which would require at least a 10-gauge wire to accommodate this large power distribution.[14]

2.1.2 Torque Cancelling Motor

After implementing a bearing assembly to prevent the propulsion system from rotating, there remains a small torque of 1 Nm as a result of friction in the bearing and shaft assembly. This torque will be offset by using a small electric motor that is connected in the assembly. The electric motor will need to supply a torque that matches the friction and run at the exact speed of the system from stationary to full speed rotation of 2 RPM. In order to run at the correct speed and torque, a custom gearbox will need to be designed. The Parvalux PM8S was chosen as a representative motor type because it has a low-end torque of 0.3-Nm which is beneficial when the friction is the lowest at the beginning of the system rotation.[15] It uses a DC permanent magnet motor which tends to be smaller and lighter than the AC motors. There is a risk of the motor failing and causing the propulsion system to slowly start spinning-up along with the artificial gravity system. Allowing the propulsion system to spin could cause the trajectory of the spaceship to be off and the additional stress from the spin could damage the solar panels. If that were to happen the artificial gravity system would need to be spun-down so that the motor could be repaired or replaced. To mitigate this potential problem a second motor will be installed in the bearing assembly as backup.

Figure 6 – Parvalux DC Brushless Motor[15]

[14] See RASCAL Power and Wiring Sizing PDF
[15] "Parvalux DC Brushless Motors."

Motor	Type	Mass (kg)	Power Range (W)	Torque Range (Nm)	Speed Range (RPM)	Technological Readiness Level
Siemens Simotics S-1FT7[16]	DC Permanent Magnet	Unknown	850-1700	1.4-108	1500-6000	TRL 9
Parvalux PM8S[17]	DC Permanent Magnet	1.1	13-48	0.3-1.9	21-970	TRL 9
Parvalux SD 21 LWS[11]	AC 1 Phase Induction	5.45	8	1.0-100	0.22-56.5	TRL 9
IronHorse Series MTG[18]	DC Gear Motor	1.81	17.1-54.9	2.93-5.65	8.4-114	TRL 9

Table 3 – Torque Cancelling Motor Trade Study

2.2 Expandable Shaft

A key innovation for this design is the expanding shafts to position and support the pods for rotation. Expanding from the central hub, they will serve as the link between the two pods and allow transfer of supplies from the storage pod to the habitat pod. Likewise, waste mass can be moved from the habitat pod to the storage pod to maintain mass balance for the rotating system. Material and equipment movement between the pods will be via a robotic transport system that uses the shaft. By using a robotic system, the connecting shaft size and environmental requirements are minimized along with overall mass. The expandable shafts design is the most challenging portion of this project. It must be compactly stowed, extend and retract reliably, and support both tension loads during rotation and bending loads imposed during electric propulsion thrust and reorientation. It must have minimum mass and good damping characteristics to minimize dynamic motions during deployment and use.

2.2.1 Shaft Supports

Since the shaft system must expand and contract, that limits the materials that can be selected for the shaft's supports. Traditional metal trusses were not an option for this reason. This left newer technologies that are currently being developed and refined thus running the risk of not being ready for the 2029 deadline.

[16] "SIMOTICS S-1FT7 Servomotors."
[17] "Parvalux DC Brushless Motors."
[18] "IronHorse Series MTG."

	Bi-Stable Reeled Composite (BRC)[19]	Telescopic[20]	Self-Building Truss[21]	Inflatable[22]	Cable[23]
Achieve 84.6 Meter Length	Yes	Yes	Yes	Yes	Yes
Stable at 84.6 Meters	Yes	Yes	Yes	Unknown	Yes, if properly anchored
Stable Under Torsion	Yes, with bracing	Yes	Yes	Unknown	No
Material	Carbon Fiber	Composite	Metal	Kevlar	Metal
Mass	Light	Moderate	Heavy	Moderate	Moderate
Technological Readiness Level	TRL 7	TRL 8	TRL 6	TRL 7	TRL 9

Table 4 – Expandable Systems Trade Study

	RolaTube[19]	Astrotube[25]	ROCCOR[24]
84.6 Meter Length	Yes	No	No
Stable at 84.6 Meters	Yes	No	No
Mass	436 g/m^2	Unknown	0.66 kg/m
Deployment	Reel Motor	Reel Motor	Reel Motor
Cost	Lower than traditional space booms	Lower than traditional space booms	Unknown
Rigidization	Uses BRC properties	Embedded Conductors	Embedded Conductors
Material	Carbon PEEK	Carbon Fiber	Carbon Fiber
Technological Readiness	TRL 7	TRL 6	TRL 5

Table 5 – BRC Trade Study

Based on the trade study above, the bi-stable reeled composite (BRC) for its high strength and lightweight qualities. There are several options for BRC products that have been used in space before, but nothing to the extent that this system requires. RolaTube[19] was chosen as a representative product because it has more experience with creating long stable structures in space whereas it competitors have only been able create stable structures that span about 1-meter.[25] A similar concept to the BRC has been used in a prototype design for the solar panels on the ISS called Roll-Out Solar Array (ROSA). ROSA is stored as a rolled one-piece slit-tube boom in a

[19] "RolaTube | Expeditionary Systems."
[20] "Telescopic Tube Masts."
[21] Bell, Larry. "Space Trusses."
[22] "BEAM Attached to the International Space Station."
[23] "Steel Cable."
[24] "ROCCOR Booms."
[25] "Oxford Space Systems AstroTube Boom Overview."

trunk until deployment. Upon deployment, it uses the strain energy stored in the boom to assist in the deployment process. The booms then provide the array with structural support and strength while deployed in the environment of space.[26] This is analogous to the process that the expandable shaft concept will use to push the two pods out from the central hub, just on a much larger scale. Project Daedalus will use the BRC's stored strain energy and small electric motors to start the pods movement from the hub. Then the stored strain energy in the booms will push the pods out to full extension. The motors will then be used again to retract the supports back into the central hub upon transition back into the hammerhead configuration. An Ohio Electric DC motors has been chosen as a reference and using this motor, the expansion and contraction will be able to occur in approximately 20 minutes. To help increase rigidity in the shaft, the shaft will be pressurized to 101 kilopascals. The pressurized shaft will help resist bending loads and buckling. The shaft will have a length of 84.6-meters which will produce a simulated Mars gravity when the system is rotated at 2 RPM. This length and rotational speed should provide a comfortable environment for the astronauts with modest Coriolis effect.[27]

The supports will need to be positioned in such a way that the shaft is strong and stable enough to support the loads seen during launch, expansion/contraction, and rotation while minimizing the mass being added to the system. If the spacecraft were to launch from cis-lunar orbit fully expanded the bending stress on the system would be 27.17-MPa and even with a factor of safety of 2 this is still below the maximum bending stress allowed by the BRC. However, the team feels that this static case number does not adequately account for stresses due to dynamic that the system would see during chemical propulsion operation. Additionally, the team is concerned with the vibrational modes the system would see from the imbalance of the thrusters which could cause the BRC to reach its natural frequency leading to fractures and permanent deformation. Therefore, the team believes that it would be a safer option to launch from cis-lunar orbit while the system is in the hammerhead configuration since it experiences a lower bending stress of 1.61-MPa. Project Daedalus would then wait to expand until it has transitioned to electric thrust where the bending stress will only be 0.031-MPa when fully expanded and any dynamic forces commensurately lower.

Chemical Thrust – Hammerhead Configuration, No Rotation	
Force of Chemical Burn (N)	890
Acceleration of Chemical Burn (m/s^2)	7.86×10^{-3}
Force on Pods (N)	196.5 (Compression)
Moment (Nm)	982.5
Bending Stress (MPa)	0.16

Table 6 – Chemical Thrust Loads: Hammerhead, No Rotation[28]

[26] "Roll-Out Solar Array (ROSA)."
[27] Hall, Theodore W. " Artificial Gravity in Theory and Practice."
[28] See RASCAL System Loads PDF

Chemical Thrust – Transit Configuration, No Rotation	
Force of Chemical Burn (N)	890
Acceleration of Chemical Burn (m/s^2)	7.86×10^{-3}
Force on Pods (N)	196.5 (Compression)
Moment (Nm)	1.66×10^4
Bending Stress (MPa)	2.71

Table 7 – Chemical Thrust Loads: Transit, No Rotation[28]

Chemical Thrust – Transit Configuration, Rotation	
Force of Chemical Burn (N)	890
Acceleration of Chemical Burn (m/s^2)	7.86×10^{-3}
Force on Pods (N)	9.23×10^4 (Tension)

Table 8 – Chemical Thrust Loads: Transit, Rotation[28]

Electric Thrust – Hammerhead Configuration, No Rotation	
Force of Electric Thrust (N)	8.75
Force on Pods (N)	2.27 (Compression)
Moment (Nm)	11.33
Bending Stress (MPa)	$1.85 * 10^{-3}$

Table 9 – Electric Thrust Loads: Hammerhead, No Rotation[28]

Electric Thrust – Transit Configuration, No Rotation	
Force of Electric Thrust (N)	8.75
Force on Pods (N)	2.27(Compression)
Moment (Nm)	191.6
Bending Stress (MPa)	0.031

Table 10 – Electric Thrust Loads: Transit, No Rotation[28]

Electric Thrust – Transit Configuration, Rotation	
Force of Electric Thrust(N)	8.75
Force on Pods (N)	9.27×10^4 (Tension)

Table 11 – Electric Thrust Loads: Transit, Rotation[28]

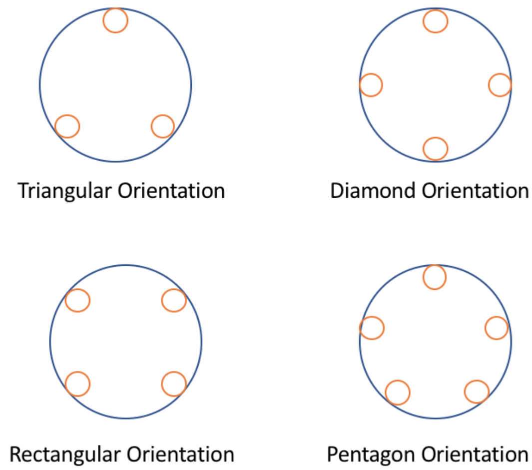

Figure 7 – Support Orientations

In an effort to get the supports positioned in a way that will help make the shaft strong and stable enough to support the loads seen in the tables above, finite element analysis (FEA) was conducted using Solidworks. The FEA ran four support orientations: 1.) Triangle, 2.) Diamond, 3.) Rectangle, and 4.) Pentagon. Each support orientation was analyzed using an applied torque of 456.8 Newton-meters and a variety of support dimensions for the tube's diameter and thickness. Figure 8 shows some of the scenarios conducted in Solidworks, notice how eventually all of the support configurations converge on one another if given a large enough tube thickness.

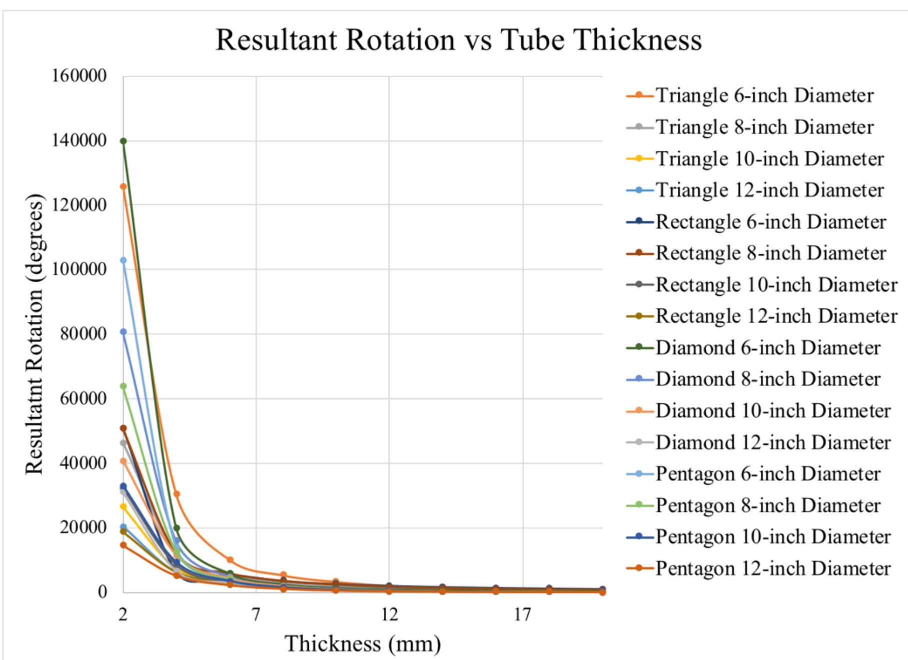

Figure 8 – Solidworks FEA Support Orientations Resultant Rotation

Based on the results from Figure 8, the team chose to use the rectangular support orientation even though the pentagon configuration had slightly better resultant orientation results. This better resultant rotational result did not justify the additional mass that an extra support would add to the system thus making rectangular the better option. With the support orientation narrowed down to one configuration, it became necessary to run scenarios of differing tube diameter and thickness while in the rectangular orientation to further determine the optimum support. Again, the team used an applied torque of 456.8 Newton-meters but this time ran it on tube diameters ranging from 6-inches to 12-inches and with tube thicknesses between 2-millimeters and 20-millimeters. Figure 9 shows the results of the resultant rotation for these scenarios.

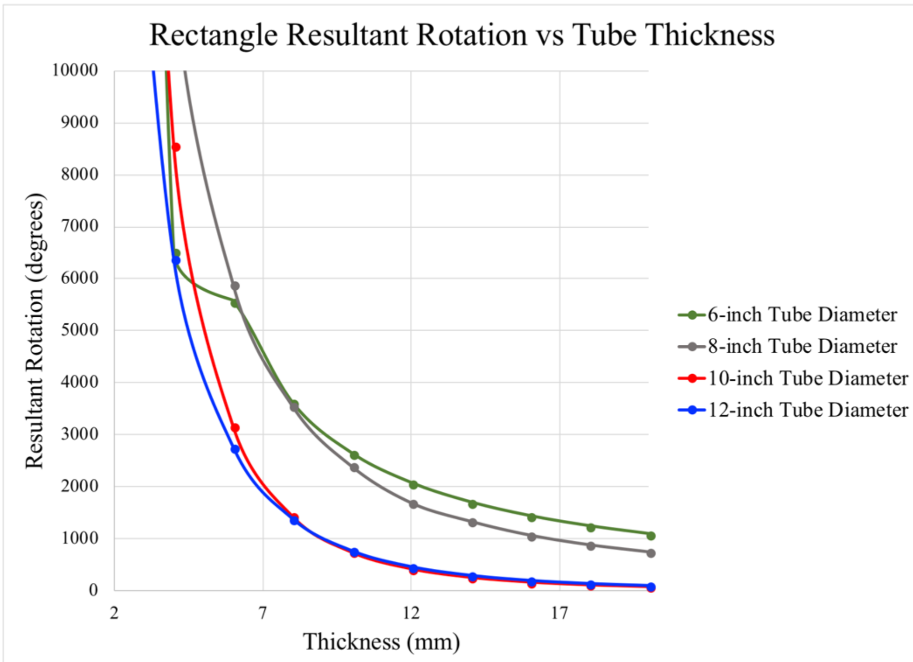

Figure 9 – Rectangular Orientation Resultant Rotation with Varying Dimensions

Figure 9 clearly shows that the tube diameters of 10-inch and 12-inch are the better choice and that eventually 10-inches equals 12-inch in its resultant rotation. This means that there is no justification for going for the heavier 12-inch diameter when the 10-inch will be sufficient when it has a tube thickness of 14-millimeters. At these dimensions, the resultant rotation is 271 degrees which is still too large for the system to be able to operate therefore additional bracing will need to be added to the shaft to make it more rigid.

A similar protocol was conducted with the bracing FEA that was done with the supports. The first step in this analysis was to determine how many brace sets would be necessary per side for the system to become stable during rotation. With that goal in mind, the team ran analysis on braces sets ranging from 1 set to 10 sets using an applied torque of 456.8 Newton-meters to simulate the force on the system during spin-up. The results from this analysis can be seen in Figure 10 which show that eventually if enough brace sets are added the resultant rotation will level off and become stagnant. This point occurs at seven braces sets so the team decided that this was the optimum number of brace sets needed giving a resultant rotation of 5.01 degrees.

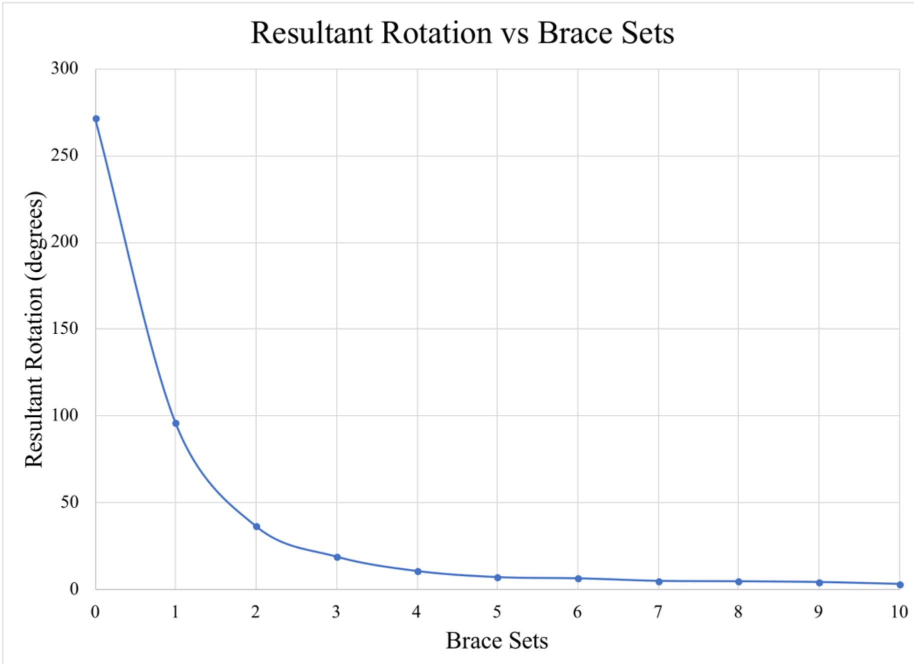

Figure 10 – Resultant Rotation FEA Results for Brace Sets

In an attempt to make the resultant rotation closer to zero, the team ran more FEA analysis on the sizing for the braces similar to the down-select procedure don for rectangular orientation. Using this procedure, the team found that the optimum bracing tube diameter would be 4-inches with a thickness of 6-millimeters. This gave a resultant rotation of 1.99 degrees.

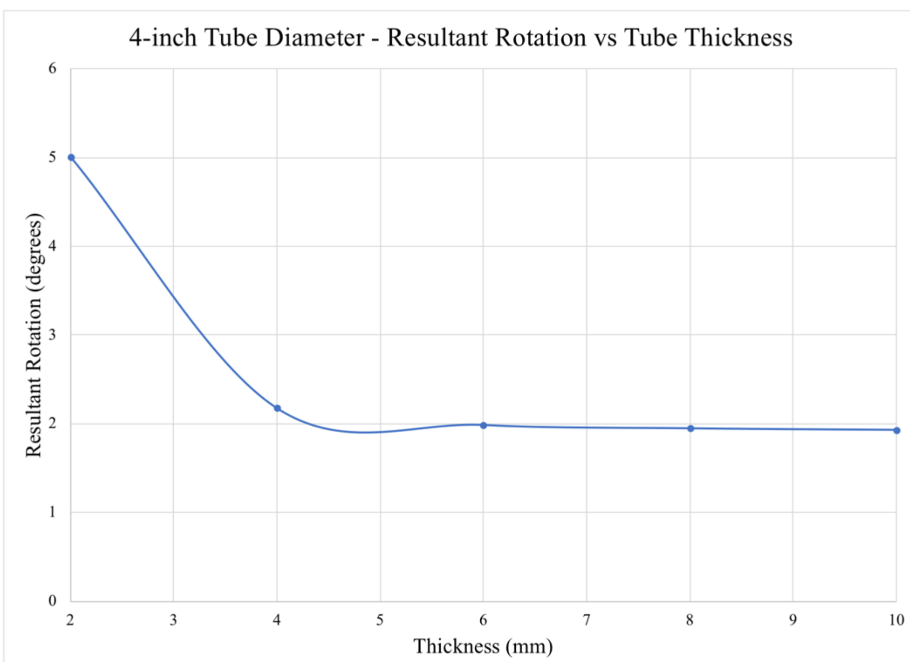

Figure 11 – Resultant Rotation for Brace Dimensions Optimization

2.2.2 Shaft Shroud

The expandable shaft's shroud will be simultaneously deployed with the BRC booms to maintain a controlled environment in the shaft at all times. The shroud must be capable of providing a pressurized environment as well as providing protection from the outside space environment. It will use layers of Kevlar KM2 and thermoplastic polyurethane (TPU) sheeting with an additional layer of insulation on the outside to prevent UV degradation. The TPU sheeting will be used to create an airtight environment in the shaft while the Kevlar will provide the necessary strength. The shroud will need to be collapsible but this must be done in a way that the Kevlar will not be permanently deformed. A solution to this deformation is two-fold: 1) maintain air between the gaps of the shroud when stored to prevent 100% compressibility, and 2) fold the shroud using origami folding techniques, as shown in Figure 12, which will allow for compact storage and add additional rigidity to the expandable shaft when fully expanded. By utilizing pre-fabricated fractal folds, the shroud can safely expand and contract without material fatigue issues.[29] When the shroud is compacted during the hammerhead configuration, it will require a length of 2 meters inside the central hub per side. While it is in this compact state, the shroud will have an inner diameter of 1.88 meters and an outer diameter of 2.12 meters instead of the 2-meter inner diameter when fully expanded. This change in diameter is the result of the way that the shroud is folded when using the origami techniques seen in Figure 12. Figure 13 shows a cross sectional view of central hub when the shroud is in this compact state and shows the dimensions necessary for storage.

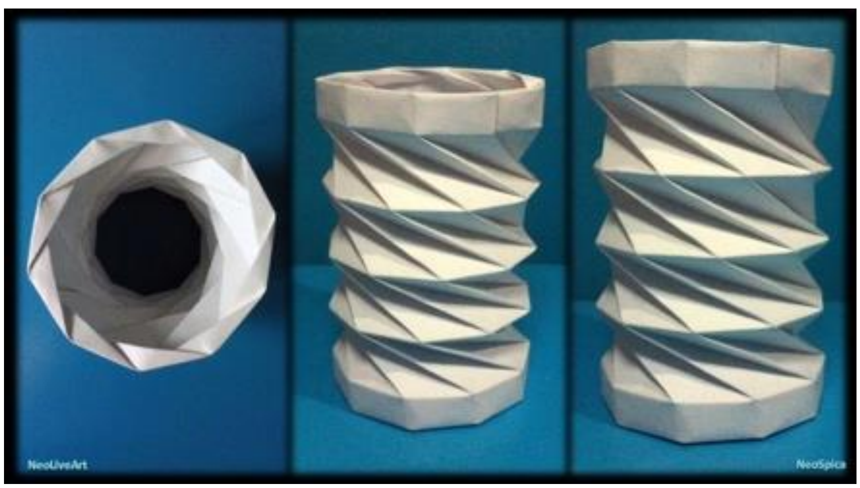

Figure 12 – Origami Folding Technique[29]

[29] Ma, Jiayao. "Thin-Walled Tubes with Pre-Folded Origami Patterns as Energy Absorption Devices."

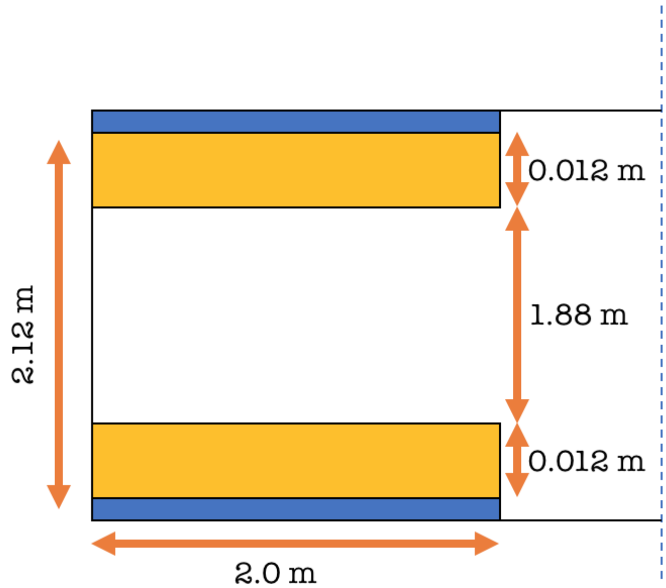

Figure 13 – Cross-Section of Central Hub with Compacted Shroud

The shroud will have to endure the harsh space environment across its design service life When the shaft is expanded the shroud will see temperatures ranging from -157°C to 121°C and face solar irradiation.[30] However, since it is in space, conduction effects are minimal and convection cannot occur without a medium to absorb heat. In addition to the thermal exposure, the shroud could experience micrometeorite impacts. Since Project Daedalus has no ability to stop debris from impacting the spacecraft, the goal is to let them fly through the shroud and have the robotic system patch small holes as necessary.

Kevlar is being used to help protect the interior of the shroud while a multi-layer insulation cover is being made with various layers of aluminized Beta Cloth, aluminized Kapton, aluminized Mylar, and Nomex netting layers to reduce conduction between the materials. NOMEX was chosen over Dacron netting since the Dacron can shrink at certain temperatures that are seen in the space environment and the NOMEX is more flexible which is necessary in an expandable system. The proposed layering scheme for the multi-layer insulation is aluminized Beta Cloth on the outside with 20 layers of aluminized Mylar with Nomex netting between the reflective layers to reduce the conduction effects. This will allow the shroud to reject 90-99% of the sun's radiation and allow the interior of the shroud to experience less extreme temperature changes.[31]This will allow the interior of the shroud to experience less extreme temperature changes as well as protect the Kevlar.

Each layer will be sewn together in a pattern fit for collapsing. The thread exposed to the space environment will be glass thread coated with PTFE Teflon due to its high heat tolerance and resistance to atomic oxygen. The interior threading will be NOMEX for high thermal resistance and material uniformity. An inner cover of aluminized Kapton with the aluminized side facing the MLI and the MLI will be secured to the Kevlar using with hook and pile fasteners. The fasteners will be constructed of NOMEX as well because of its ability to reduce the conduction effects to the Kevlar. The multi-layer insulation (MLI) has a lifespan of 5 years in operational use and 15 years in nonoperational use which means that it may need to be replaced in the later trips to Mars.

[30] "ISS Space Environmental Effects."
[31] "Multi-Layer Insulation for the Alpha Magnetic Spectrometer."

	Mass/Area (kg/m^2)	Surface Area (m^2)	Mass (kg)	Thickness(mm)
Outer Cover Aluminized Beta Cloth	0.237	1063.115	251.9582	0.2
Reflective outer layer Aluminized Kapton x 2	0.011	1063.115	23.38853	0.0076
Reflector layer x 20 Aluminized Mylar	0.007	1063.115	148.8361	0.0051
Separator x 20 Nomex	0.0063	1063.115	133.9525	0.16
Total			**558.1354**	**3.5172**

Table 12 – Multi-Layer Insulation Mass and Sizing

2.3 Habitat Pod and Storage Pod Rotation

To achieve artificial gravity similar to Mars, the system must spin at 2 RPM. Two thrusters will be attached to each pod with one thruster on each side of the pod facing in opposite directions like in Figure 14. One thruster on each pod will fire to create the required torque for rotation which is 456.8 Newton-meters. This torque will spin-up the system to 2 RPM in 28-hours. The short spin-up time is necessary to maintain a Mars level gravity for a majority of the mission. The bearing assembly will allow the system to rotate freely at this speed until Mars orbital insertion at which point the second set of thrusters will fire and bring the system to a stop in a similar time.

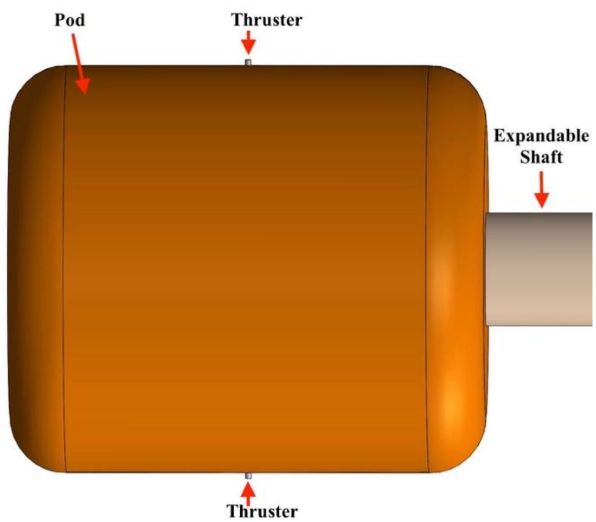

Figure 14 – Thruster Placement

Thruster Type (Propellant)	Optimal Spin-Up Time (hr.)	Force per Thruster (N)	Total Thruster Mass (kg)	Power to Operate (kW)
Cold Gas (Nitrogen)[32]	17	8.9	11861	0.04
Hall Effect X3 (Xenon)[33]	28	5.4	1268	204
Hall Effect HERMeS TDU-1 (Xenon)[34]	250	0.6	699	25
Chemical (Hydrazine)[35]	6.7	22	2796	0.082

Table 13 – Thruster Trade Study

Several thrusters were analyzed to determine which would be able to spin-up the system in the desired time while minimizing the mass. A major problem was that the two criteria were not optimized at the same point. The cold nitrogen gas thruster was too inefficient for the large inertial mass of this spacecraft. The X3 Hall Effect thruster was found to be the best for this mission considering it allowed the mass of the thrusters to be significantly smaller than the other thruster options with the trade-off being the spin-up time of 28-hours.[33] The 28-hours will still allow the astronauts to maintain a Mars level gravity for a majority of the mission though. Another Hall Effect thruster, HERMeS TDU-1, was analyzed in the event that the mass in the X3 thruster will push the spacecraft over the mass limit. The HERMeS thruster will reduce the thruster mass by half and the amount of power needed to operate, but the spin-up time would be 250 hours which is assessed as being too long.[34]

2.4 Robotic Systems

There will be two robotic systems in the spacecraft, one for the expandable shaft and another for the storage pod. The robotic system used in the expandable shaft will be required to make post extension connections with Velcro to maintain a contact between the BRC booms and the shroud in order to increase the stability of the fully extended system. It will also need to secure the bracing between the BRC supports post-extension to help maintain torsional stability. The robot will be required to unfasten all the connections and remove the bracing prior to contraction of the pod system. This requires a certain level of fine motor skills. This same robotic system will be required to transport items between the pods for the astronauts.

[32] Moog Inc. “Cold Gas Thrusters.”
[33] Hall, Scott J. “High-Power Performance of a 100-KW Class Nested Hall Thruster.”
[34] Peterson, Peter. “NASA HERMeS Hall Thruster Electrical Configuration Characterization.”
[35] “Hydrazine Thrusters.”

	Valkyrie R5[36]	Spidernaut[37]	Shadow Teleoperation Development System[38]
Capabilities	Maintenance and inspection tasks	Carrying objects	Fine motor skills and maintenance
Mass (kg)	136	272	28.9
Shaft Transit	Ladder system	Web	Similar to elevator shaft
Power Required (kW)	1.8	3.6	0.5
Technological Readiness Level	TRL 6	TRL 6	TRL 8

Table 14 – Expandable Shaft Robotic System Trade Study

Figure 15 – Shadow Teleoperation Development System[38]

The Shadow Teleoperation Development System was chosen to be the robotic system for the expandable shaft because it has the fine motor skills necessary.[38] This robotic system is comprised of a UR10 robotic arm that has a Shadow Hand attached to it. The Shadow Hand can be remotely controlled by an astronaut wearing a CyberGlove which has sensors embedded in the glove to allow the Shadow Hand to mimic what the astronaut is doing.[38] By creating a system of cameras and sensors in the shaft, the astronauts will be able to remotely make all the necessary connections and perform any maintenance needed in the shaft without having to put a spacesuit on. This robotic system can also be programmed to make the connections on its own if so desired. In order for the robot to move up and down the shaft, it will be connected to a mechanism that is attached to steel cabling. The mechanism will be moved up and down the shaft using a motor and when the shaft is in the hammerhead configuration the cabling will be reeled up.

Another robotic system will be needed in the storage pod to maintain organization of the supplies. This robot will be similar to industrial warehouse robots with the main function being to scan, organize, and transport items from shelves to the transport bag that is attached to the robotic system in the expandable shaft. A machine learning robot is perfect for this operation and will only require a simple command now and then to perform routine checks.

36 Kisliuk, Erin. "R5."
37 "NASA's Spidernaut Robots Will Go Where Humans Dare Not."
38 "Universal Robotics."

Figure 16 – Machine Learning Robot

2.5 Habitat and Storage Pods

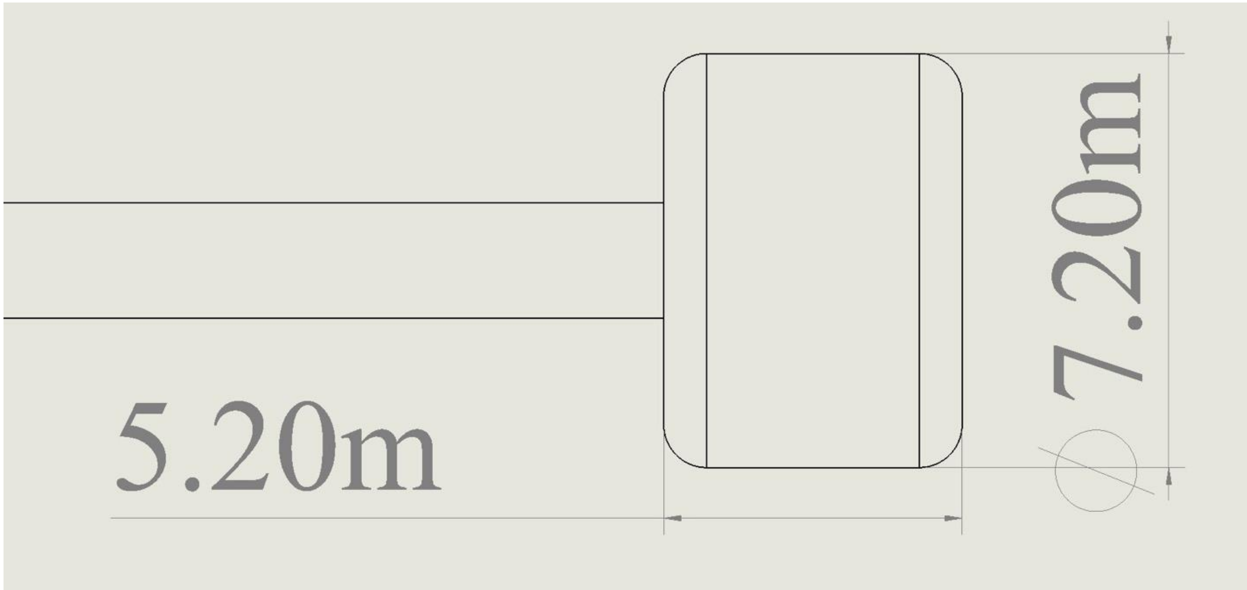

Figure 17 – Pod Dimensions

The two pods used in this design will be adapted from the current NASA baseline habitat which has a 7.2-meter diameter and 5.2-meter height. It is desirable to have maximum re-use of baseline habitat structural and systems design for both pods. Equipment and systems not requiring direct human contact can be placed within the storage pod along with most of the provisions. The storage pod will hold the high mass items like the water and waste in order to free up space on the crew side. A small portion of food and water will be kept in the habitat pod in case of emergency to allow time to de-spin and reconfigure the pods. The storage pod will not require the same floor plan as the habitat pod and can be optimized for its primary purpose. It will be a shell of the crewed habitat with a storage system of shelving to properly organize the equipment and provisions. Both pods will have environmental control and life support systems. This preserves the stored items and provides a “lifeboat” capability in case there is an emergency.

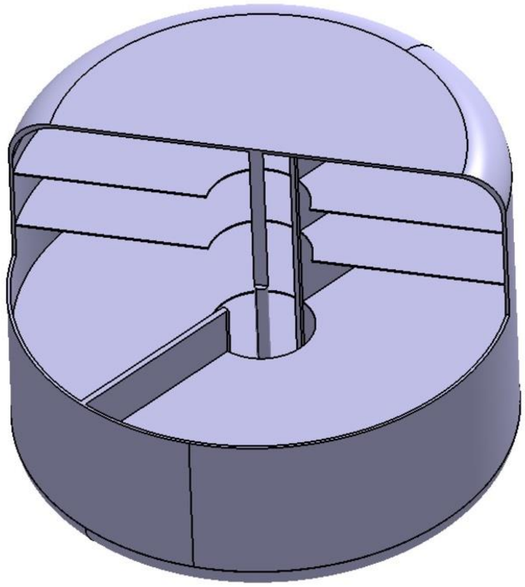

Figure 18 – Cross-Sectional View of Storage Pod

2.6 System Connections

In order to maintain the system, there will be a variety of connections. The first connection will be between the supports and the pods. This connection will be maintained through the use of a mechanical joint similar to Figure 19. Half of the joint will be bolted onto the pods and the other will be bolted into the BRC. These two halves will then be joined with bolts to complete the connections.

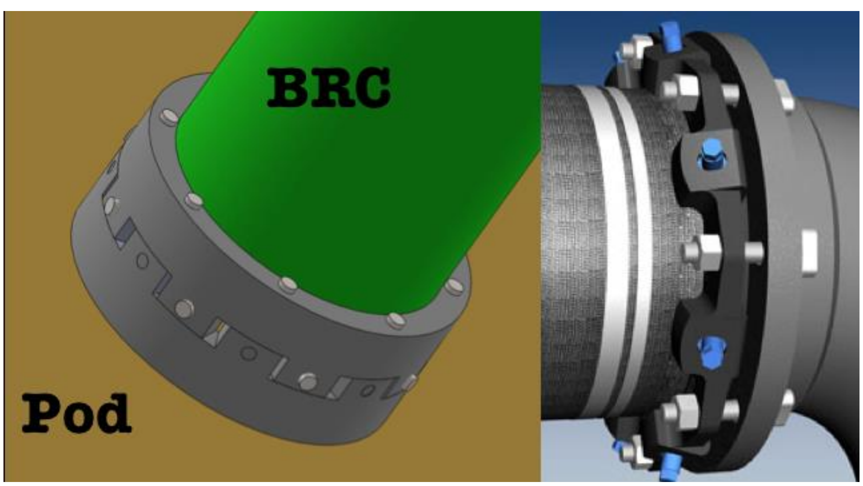

Figure 19 – Mechanical Joint for Supports and Pods

Another connection will occur between the shroud and the pods/hub. Since the shroud will have several loads placed upon it, the team decided that it would be best to use something similar to the NASA common berthing mechanism to ensure that the connection does not separate. The NASA common berthing mechanism has been designed to join the shuttle to the space station so it should be capable of withstanding the loads placed upon this system too. The main part of the connection will be bolted onto the pods and hub and the smaller connection will be secured to the shroud. The smaller connection will then just hook onto the main connection to form a seal.

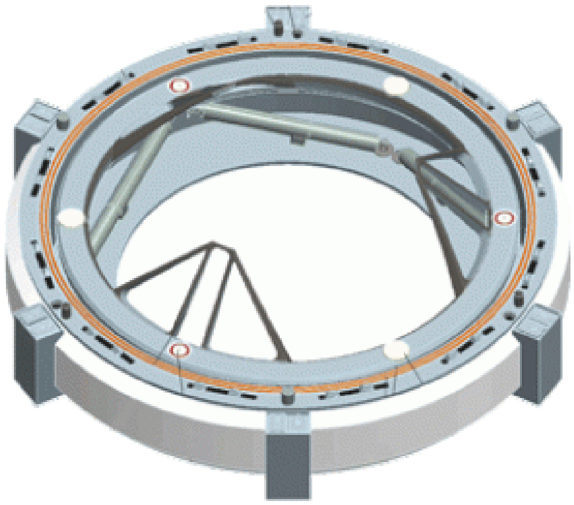

Figure 20 – NASA Common Berthing Mechanism

For the connection between the supports and the brace sets, it will be comprised of t-like connectors, see Figure 21. These connections will already be installed on the supports when in the hammerhead configuration and the robot will only need to slide them into position when in the transit configuration. These connections will be made out of heavy duty plastic or composite to help reduce the mass of the system.

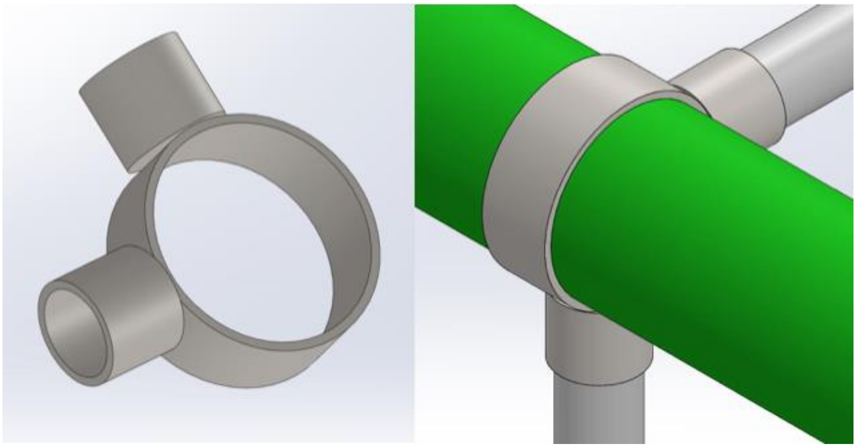

Figure 21 – Support and Brace Set Connections

The final connection that will need to be made in the shaft will be between the supports and the shroud. This connection will use Velcro strips wrapped around the support by the robotic system after the shaft has expanded into the transit configuration.

2.7 Mass and Size Estimates

Since Project Daedalus uses a two-pod design, it will need to have systems in place to ensure proper mass balance at all times. The current mass estimates are in Table 15. There are several options to consider to keep the mass balanced. The first being to use a pipe filled with water that is capable of auto-balancing the system. Another option is by reeling one of the shafts in by a small increment until the system regains balance. The final option is to have two robotic systems that run parallel and in opposite directions moving the same amount of mass to each pod at the same time.

Description	Mass (kg)
Habitat Pod	22,555
Storage Pod	22,598
BRC Supports and Reel Boxes[39]	200
Shaft Shroud	2,257
Robotic System – Shaft	28.9
Robotic System – Storage Pod	25
Central Hub	353.85
Bearing Assembly	627
Thruster and Thruster Fuel[40]	1,268
Torque Cancelling Motor[41]	1.5
Expansion Motor[42]	15.42
Total System Mass (kg)	**49,911**

Table 15 – Mass Estimates

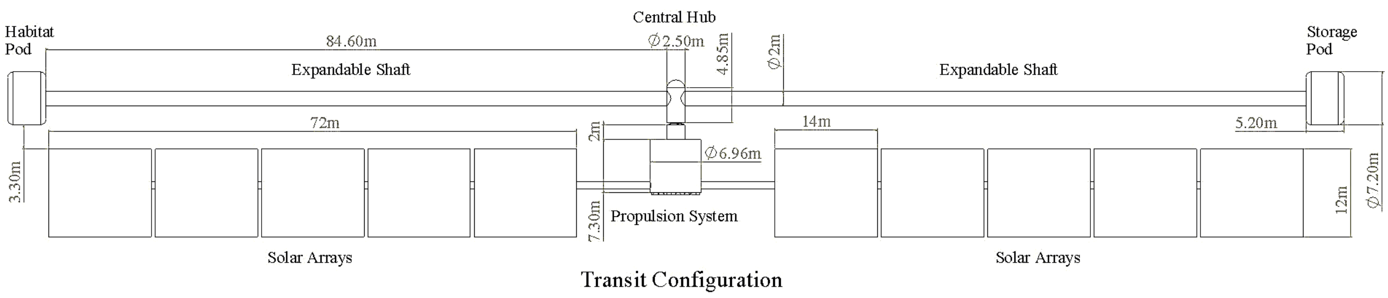

Figure 22 – Transit Configuration Dimensioned

[39] "RolaTube | Expeditionary Systems."
[40] Peterson, Peter. "NASA HERMeS Hall Thruster Electrical Configuration Characterization."
[41] "Parvalux DC Brushless Motors."
[42] "Brushless Motors."

3.0 Logistics

The system will need to launch in two SLS Black 2 rockets. One launch will have the hammerhead assembly and supplies while the second will carry the propulsion system. This fits within NASA's baseline launch schedule which had two planned launches for the Mars mission. In Figure 22, it shows how the hammerhead assembly will fit within the SLS Block 2 but does not show all of the supporting material that will be necessary to keep the assembly secure during the launch.

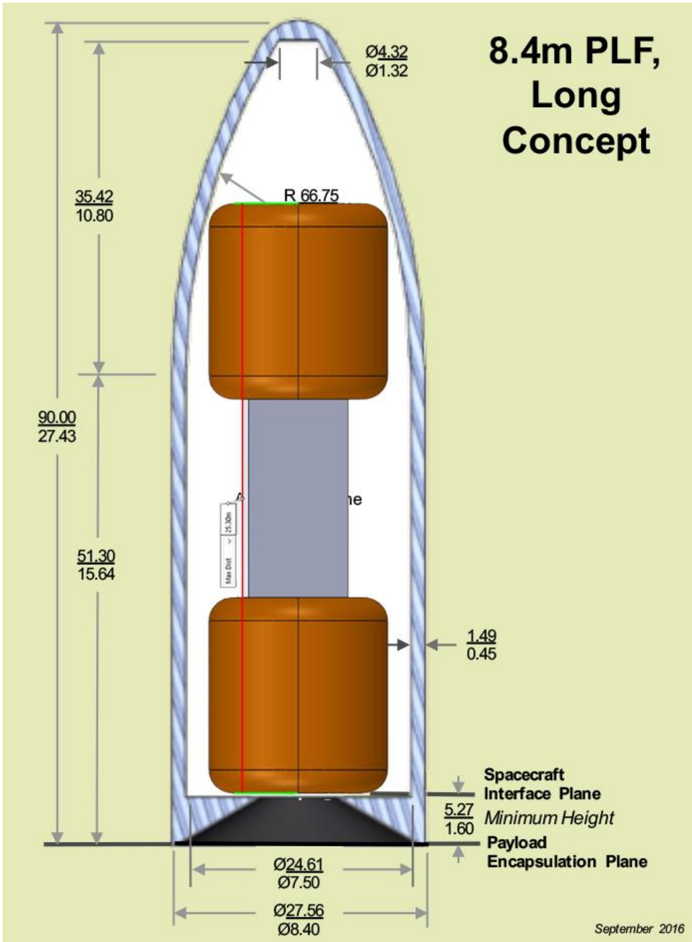

Figure 23 – Hammerhead Assembly Inside SLS Block 2

4.0 Budget

A budget was created using current and past NASA projects as baselines to help assess a realistic cost of implementing this spacecraft for the missions to Mars. The budget below describes the additional funding that is required for the changes that the artificial gravity system has made to the baseline spacecraft. It is also making the assumption that a SLS Block 2B is how the equipment and supplies will reach Lunar orbit. By assuming that it is a SLS Block 2B rocket, Project Daedalus will be able to launch in one rocket. Additional budget expenditures occur in technological development to ensure that all technologies used in this concept will meet the 2029 deadline. Some key technological readiness risks are in the use of the origami folding techniques used in compacting the shroud. This technique is fairly new and has not been attempted on this scale, so testing will be necessary to ensure that it will perform as needed for this mission. Another risk is that the clearance in the expandable shaft may not be quite enough for the current spacesuits that astronauts are using. At current estimates the amount of space available to transverse the central hub during an emergency situation is around 1.4-meters, the astronauts will need approximately 1.7-meters of clearance to move around without ducking.[43] If money is used to research and test more compact spacesuits by 2029, this will eliminate any potential problems that may arise from lack of clearance in the shaft. Finally, additional budget expenditure on the shaft's robotic system's development will ensure that all systems are capable of operating in a space environment. The current robotic system has only ever been used on Earth which poses a risk that it may not perform properly when in space. However, by using money to conduct experiments on it, it will ensure that the system becomes space rated by 2029.

[43] "EXTRAVEHICULAR ACTIVITY (EVA)."

Object	Assumptions	Cost ($)
Engineering Development	Funds needed for engineering design, prototype development, and testing	170,000,000
Pressure Control System	Assuming a separate pressure control system will be necessary for the expandable shaft	2,000,000
BRC Material		33,000
Connector for BRC and Pods	Assuming a mechanical joint is used	32,000
BRC Brace Connections	Assuming cross connector	24,000
Connector for Cover and Hub/Pods	Assuming common berthing mechanism like NASA uses[44]	20,000,000
Shroud	Assuming Kevlar/TPU[45]	221,000
Expansion/Retraction Motor	Assuming Ohio Electric D482273X7088[46]	29,000
Torque Cancelling Motor	Assuming Parvalux PM8S and additional funds needed to space rate the motor[47]	20,000
Robotic Track	Assuming cost of steel cabling that spans the expandable shaft and this includes the cost of mechanism to go up/down	60,000
Robotic System – Expandable Shaft	Assuming cost of robotic arm, glove, and sensors[48]	400,000
Robotic System – Storage Pod	Assuming it costs similar to the robotic arm used in shaft robotic system	200,000
Central Hub Structure		416,000
Bearing Assembly		233,000
Hall Effect Thrusters	Assuming X3 Hall Effect Thruster[49]	320,000
Xenon Fuel	Assuming for 3 round trips at $850/kg[50]	918,000
Storage Pod Shell and Organization System	Assuming it costs similar to Leonardo, Raffaello, and Donatello modules on the ISS[51]	230,000,000
Total Additional Cost from Baseline ($)		**424,906,000**

Table 6 – Additional Budget Required

5.0 Risks and Mitigation

This system has several risks that will need to be accounted for before it can be used in a mission to Mars. The most significant being that the mass balance cannot be more than 10

[44] Illi, Erik. "Space Station. Freedom Common Berthing Mechanism."
[45] "Kevlar® Brand | DuPont USA."
[46] "Brushless Motors."
[47] "Parvalux DC Brushless Motors."
[48] "Universal Robotics."
[49] Peterson, Peter. "NASA HERMeS Hall Thruster Electrical Configuration Characterization."
[50] Hall, Scott J. "High-Power Performance of a 100-KW Class Nested Hall Thruster."
[51] "Module List - International Space Station."

centimeters off of the center of mass if the system is to operate properly. Currently, the system's center of mass is -8.14 centimeters from the center. This is fairly close to the upper limit of 10 centimeters which means that if anything changes inside the pods to shift the center of mass there may be a catastrophic problem. As mentioned in section 2.7, this can be mitigated by using a water pipe, varying arm lengths, or a dual robotic system. The next potential issue is that there may not be enough clearance between the solar arrays and the bottom of the pods. When the system is static there is a clearance of 2.18 meters, however, when the system is under a rotational load the pods have a displacement of 0.575 meters. This leaves the system with a clearance of 1.605 meters which may not be enough when a dynamic analysis is conducted. The team recommends that a dynamic analysis is done to see if this clearance will be enough to allow the system to function properly. If it is shown to not be sufficient, the central hub will need to be pushed out further to increase the distance between the two systems. The last problem in the design is the astronaut clearance inside the central hub. There currently is about 1.4 meters of clearance inside the hub which will allow the astronauts to pass through it but only when they crouch. This does not meet NASA regulations for clearances so the team suggests finding away to make the spacesuits smaller so that the astronauts will be capable of traveling inside the hub without ducking.

6.0 NASA Project Integration

This proposed design is not only limited to its ability to get astronauts to Mars but can also be used in other NASA projects. An adaptation can be made to the ISS to allow for the space station to rotate giving the astronauts stationed there gravity while they work and live. This will allow the crew to be able to stay on station for longer periods of time without the damage to their health. Micro-gravity experiments will still be able to be performed in a non-spinning section while the living quarter will be in the spinning section. Technology from this system will also be able to help missions like the asteroid redirect mission, by using the BRC for a deployable to help grab boulders from asteroids, and the Orion mission in which the two pod design is used to create gravity.

7.0 Conclusion

Project Daedalus' concept is innovative in that it proposes to use two pods instead of a single habitat and connects them via an expandable shaft. The expandable shafts' capabilities reduce the overall mass of the craft as compared to hard conventional structures. Current concepts use permanent metal boom structures for support in the lever arm of any rotational system. The proposed design uses new materials in novel configurations and takes advantage of robotic technologies to optimize the overall system mass. It also meets all of the requirements set in Theme 1 and 2. The pods, central hub, and propulsion system will be capable of launching on a block 2B SLS since the overall size and mass of the system will be under the constraints set by the payload bay of the block 2B rocket. The pod system has a mass under the 50-ton limit that is set by the propulsion system which means that the propulsion system will be capable of transporting the spacecraft to a 5-day sol Mars orbit and come back to a cis-lunar orbit. The power needs of this system will be sufficiently supported by the 750-kW beginning of life solar arrays and still be functional when the solar arrays only produce 607-kW at end of life. Project Daedalus has been designed using materials that will be capable of meeting the minimum lifetime of 15-years in space and has the potential of lasting longer than that minimum. Based on the spacecraft's lifetime estimates, it should be capable of supporting at least 3 trips to and from Mars with the potential of being able to support additional missions. If the additional finding is used to support the key technologies that are the most risk, Project Daedalus should be ready for the 2029 deployment and operations deadline. However, in order to meet all of these requirements, Project Daedalus will need approximately $425 million in additional funding.

Overall, the team at Oklahoma State University believes that this concept is a feasible and innovative approach to getting humankind to Mars in the near future as most of the technology needed to create this concept is already available. There will need to be some refinements to the technology but these are likely to happen before the 2029 deadline.

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