A three-body spacecraft as a testbed for artificially-induced gravity research in Low Earth Orbit

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This paper presents research and design of a three-body rotating system to be used as a precursor / testbed for research of systems functionality and human physiology under different gravity variables including simulations of lunar and Martian gravitational conditions. The testbed will be a necessary step to collect data on effects of artificial gravity on spacecraft systems and human physiology helping to optimize design solutions for lunar and Martian surface habitats and artificial gravity spacecraft. It will be the first stage of the development of a Variable Gravity Research Platform in Low Earth Orbit for long-term investigations of effects of variable gravity gradients and rotationally-induced gravity simulations.Ensuring astronauts' safety during a long Mars mission and their recovery upon return is a critical requirement for mission success. Therefore, acquiring a good understanding of long-term effects of partial gravity on physiological and psychological capabilities must be fulfilled prior to the mission and a research platform to investigate partial gravity effects on humans and technical systems is needed. A Variable Gravity Research Platform that orbits the Earth in Low Earth Orbit (LEO) can address this knowledge-gap. LEO is a good location for such a facility due to proximity to Earth's surface and access to existing infrastructure and commercial activities there. The development of such a platform will require a phased approach. The first stage of it is presented in this paper. It is a testbed for the research platform which comprises two customized crew Dragons docked to a Central Hub, which in turn will dock to the Zvezda module of the International Space Station. The intent of the proposal is to utilize off-the-shelf elements to reduce development costs and time which will enable us to perform testing "tomorrow" with today's technology. To execute operations, the testbed will undock, retreat 2000m aft of the ISS and initiate rotation by firing its augmented thrusters. Then, the crewed-Dragons will tether out to the desired radius of rotation to begin test operations. Upon completion, the testbed will de-spin, retract its tethers and re-dock to the ISS. The sequence will repeat as needed. The paper also presents the test objectives of the testbed, an analysis of its strengths, weaknesses, opportunities & threats, design development and selection criteria of the constituent elements of the testbed, Concept of Operations and possible risks associated with the testbed and their respective mitigations.

Nomenclature

LEO	=	Low Earth Orbit
Testbed	=	Testbed for a Variable Gravity Research Platform in Low Earth Orbit
ConOps	=	Concept of Operations
F_c	=	Coriolis Acceleration
CCAC	=	Cross coupled angular acceleration
EVA	=	Extra vehicular activity
ECLSS	=	Environmental control and life support systems
GNC	=	Guidance and navigation control
AACS	=	Attitude and articulation control subsystem

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d_m	=	Capacity of fuel on Progress MS
dm_a	=	Mass of fuel spent
F	=	Force applied by thruster
dt	=	Duration of thruster burn
I_{sp}	=	Specific impulse
g_0	=	Acceleration due to gravity at ground level

I. Introduction

ONE of the fundamental requirements when it comes to future manned missions to Mars is ensuring the safety of astronauts during the mission and upon their return. However, we have limited understanding of the long term effects of partial gravity on physiological and psychological aspects of the human. There is a clear knowledge gap. As part of the study done by NASA, Dr. Clement in 2015 observed that, "...we do not know, for example, whether Martian gravity level of 0.38 g is at all protective, and what gravity threshold is needed for maintaining musculoskeletal functions during long duration weightlessness."[1] Figure 1 highlights that the gravity dose - response relationship between 0-g to 1-g is unknown. Therefore, to send people to Mars for short/long term missions and even establish lunar bases, addressing this problem is paramount for ensuring safety of the pioneers.

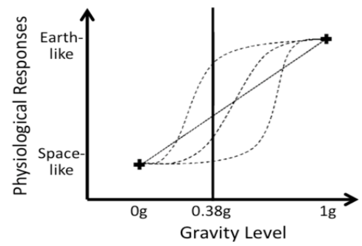


Figure 1. Hypothetical g dose-response curves. Source: Clement (2015)

II. Proposal

Outcome of the research conducted in human centrifuges is limited fluid shifts and neuro-vestibular reactions to true partial gravity conditions similar to the Moon or Mars cannot be generated there. Parabolic flights can offer partial gravity doses but the time-span of these doses are insufficient to produce feasible data. Thus, there is a need to research, design, and build a Variable Gravity Research Platform in LEO which will simulate partial gravity conditions. However, establishing such a platform will require a considerable undertaking and therefore attempting to execute it in a single step is not a feasible strategy. *This paper proposes a phased approach* with the existing human centrifuges in laboratories as Phase 1. They test short term physiological and psychological capabilities of a human body when it is exposed to a rotating environment simulating partial gravity as best much as possible. Phase 2 will be a Testbed for the Variable Gravity Research Platform which develops technical systems necessary for operating a spinning spacecraft. Phase 3 will be a testbed which tests short term adaptation of humans to spinning environments and partial gravity conditions. Phase 4 will be a complete Variable Gravity Research Platform orbiting the Earth in LEO providing knowlwdgw and experience for safe deep space travel.

This paper presents a Testbed facility for Phases 2 and 3 of this approach. It is important to note that in Phase 3, in addition to studying short term effects of partial gravity, the testbed will help to *study human adaptations to a rotating platfor*[2,3]. This investigation is aligned with TA 7.4.4 of the NASA's technology roadmaps and with NASA HRP's research objectives.

III. Scope of Paper

The design considerations presented in this paper include: ConOps of the mission, constituent elements of testbed, test objectives, understanding of time taken, forces needed, consequently the technical systems needed to achieve these forces, high level modifications to the constituent elements of the testbed, and rudimentary design of the tether system. The following topics are out of the scope of this proposal - design of subsystems of the rotating spacecraft, their functionality under partial gravity conditions, details of experiments & equipment, and interior design of the testbed.

IV. Human Factors Implications of Rotating Structures

In coming up with a preliminary design concept, the phenomena associated with rotating environments have to be understood. These will influence the design of the Testbed.

A. Coriolis Force

In experiential terms, when a person moves radially on the floor of a rotating earth based centrifuge, he/she will feel pushed to the side; when the movement is tangential, he/she will feel lighter or heavier depending on the direction of the motion. It is also important to note that the Coriolis force is independent of the radius of configuration.

B. Cross-coupled angular acceleration

Cross-coupled angular acceleration (CCAC) is a phenomenon where there is an apparent motion in yaw and roll when a person rotates his/her head in any other plane than in the axis of rotation. The mechanism behind this phenomenon is related to the canals of the vestibular system of the inner ear. The apparent motion caused by CCAC results in nausea and disorientation (Clement 2015)[1].

C. Gravity gradient

The variation in artificial gravity level as a function of distance from the center of rotation is referred as a gravity gradient. This gradient depends on the radius of the spinning system and will decrease with increase in radius. It is important to minimize the gravity gradient because it has an effect on the hydrostatic pressure along the longitudinal body axis. The hydrostatic pressure influences blood circulation to the head and from the lower body extremities and therefore affects cardiovascular system functionality (Clement 2015)[1].

V. Preliminary Design Concept

The conceptual testbed is a three-body rotating system. Two Space vehicles are tethered to a pressurized central hub as illustrated in figure 2. The central hub docks to one of ISS modules in its "rest" condition. It is a shirt-sleeve environment where a human test subject could translate in and out to the ISS directly (no EVA required). Relying on flight-proven systems and using off the shelf components offer short assembly time and low development costst. The system also provides redundancy through utilization of two identical space vehicles on either side of the central hub.

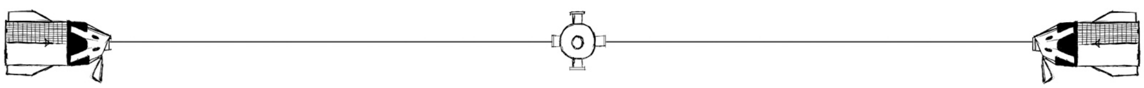


Figure 2. The preliminary design concept. Source: Author

VI. Test Objectives

Test objectives are classified as Technical and Physiological. This paper focuses on technical test objectives. The technical test objectives, which will be executed in Phase 2, include testing of: 1. ECLSS, thermal control, GNC, power supply & distribution, Propulsion & AACS, 2. Docking/transfer systems and protocols, 3. Spin-up/spin-down systems and protocols, 4. Structural stability and integrity including loads experienced during spin-up spin-down cycles and while spinning. After Phase 2, Phase 3 will be initiated with the focus on the physiological / psychological test objectives. These test objectives comprise of the following:1. Responses of a human body to coriolis forces, cross coupled accelerations, and other related forces[4], 2. Human body responses to different levels of g (thresholds)[5], 3. Human body responses to different rates of angular velocities / radii[5].

VII. SWOT analyses

Precedent cases studied during a research stage of the project included Variable-Gravity Life Science Facility (VGLSF)[6], Nautilus X, Artificial Gravity Space Excursion Vehicle (AGSEV), International Space Station. Their strengths, weaknesses, opportunities and threats were analysed. After understanding the SWOT features of the case studies, a SWOT analysis of the preliminary design Concept was conducted (Table 1).

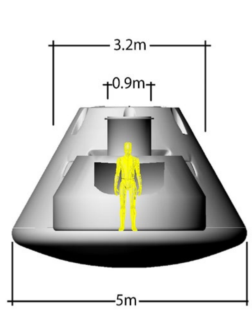
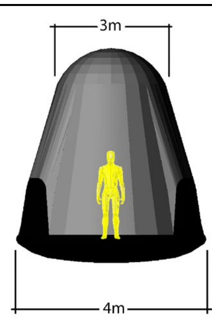
Table 1: SWOT analysis of the preliminary design concept. Source: Author.

Strength	Weakness	Opportunity	Threat
Low cost	Might need to develop a central hub module as opposed to using a pre existing one	Link to Gateway instead of ISS or both	Linking to ISS might be a bad idea since the ISS is scheduled for decommission
Low development time	SV thrusters might not be optimised for spin-up / spin-down and retreat/dock-back	Can be adapted as a low cost cislunar transit vehicle which has built in ascent / descent vehicles	In a crewed operation, emergency escape might be tricky
Pre integrated subsystems		Converted into partial gravity tourist / medical platform which allows faster return of investment	A catastrophic failure (RUD) might endanger the ISS
Flexibility and redundancy		Other modules can be docked on the free docking port on the central hub	Moon base as alternative

VIII. Selection Of Testbed Components

A. Space Vehicles

Table 2: Final two candidates for the space vehicle portion of the testbed. Source: Author

Spacecraft	Orion	Crewed Dragon
Status	Under development (2021)	Active
Crew Size	6	7
Diameter, SM (m)	5	4
Launch Mass (kg)	10,400	12,055
Power System	Solar Panels	Solar Panels
Launch cost	$500-900 million	$310 million
Design Life docked to ISS (days)		210
Free flying time	504 hours	168 hours
Sidewall angle	32	15
Habitable Volume (m3)	9	9.3
Usable dimension		

Seven potential candidates were compared to determine which one would suit best as the gravity zone to the Testbed. Lockheed Martin's Orion, HAL's Gaganyaan, Boeing's Starliner, SpaceX's Dragon, Academy of Space Technology's Shenzhou, RKK Energia's Soyuz MS and Northrup Grumman's Cygnus. The primary evaluation criteria were factors such as diameter (which translates into usable volume / crew size ratio), and status of development and operation. Two top choices selected from this set of candidates for a more detailed comparision are SpaceX's crew Dragon and Lockheed Martin's Orion. They were shortlisted for their diametrical sizes and statuses of operation amongst other evaluation criteria. Table 2 compares the two candidates. Based upon evaluation criteria such as usable volume, cost, status of operation, launch mass, the Crewed Dragon was selected as the space vehicle of choice for the Testbed.

A. The central hub

Three options were considered for the central hub based upon evaluation criteria such as availability of docking ports, status of operation, lifetime, and power system among others (Table 3).

Table 3: Comparison of the options for the central hub. Source: Author.

	Prichal (UM) + Progress MS	Cygnus (Enhanced)	Cygnus derived Gateway module
Status	Under development	Active	Under development
Length, CM + SM (m)		6.3	Unknown
Diameter, SM (m)	2.72	3.07	Unknown
Lifetime	5 years / 6 months docked	1 week to 2 years	Unknown
Launch Mass (kg)	4000 + 3290	3750	Unknown
Pressurized volume	14m3 + 7.6m3	27m3	Unknown
No. of docking ports	6 + 1	1	3
Power System	2 deployable fixed solar arrays, batteries (during free flight); via ISS (docked)	3.5 kW	Unknown

The combination of Prichal and Progress has been identified as a central hub of the Testbed considering spacecraft lifespan and availability of docking ports. However, it is important to note that the Cygnus-derived Lunar Gateway module with its three docking ports that are compatible with the crew Dragons may become a worthy contender once its specifications are published. Currently, the first choice is the Prichal/Progress combination based on the available data even though Prichal's docking ports require customization with androgynous docking ports to ensure proper compatibility with the crew Dragons.

IX. Final Design

A. Used components

The major elements used for the Testbed are Progress MS and Prichal modules shown in figure 3 and a crew Dragon shown in figure 4. A third major element is the tether system discussed later in Section C.

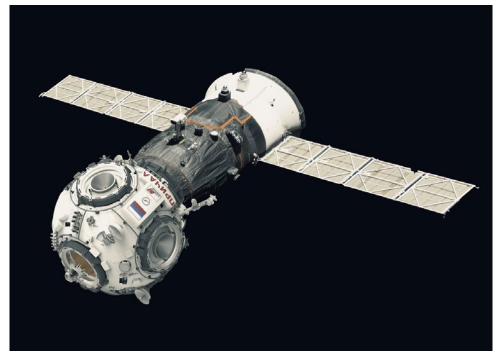


Figure 3. Progress MS + Prichal as the central hub. Source: Edited by author

B. Augmentations / customization to the components of the testbed

1. The Central hub

Out of the six Prichal's docking ports, the port adjoining the Progress is termed port A. The opposite Port B will dock to the ISS. The four remaining ports are termed C, D, E, and F. A tether system needs to be augmented to ports C and E and attach to a crew Dragon on both sides. Moreover, a collar / tunnel needs to be accomodated on port A in order to provide clearance between the ISS and the Testbed in docking position. Finally, as mentioned earlier, the off-the-shelf Prichal's docking ports will be replaced by androgynous docking ports in order to ensure compatibility with the crew Dragons.

Figure 4. Two Crew Dragon as the gravity zones. Source: SpaceX

2. The crewed Dragons

The interior of both crew Dragons will have to be customized when it is acquired as illustrated in figure 5. Almost all internal outfittings such as chairs and monitors will have to be removed. Instead, the interior will be converted into a clean volume with minimal outfittings in order to facilitate partial gravity experiments as illustrated in figure 6. Partial gravity / spinning subsystems will also have to be introduced or modified from the existing subsystems. Although interior design falls out of the scope of this paper, follow-up papers will present reports on the interior design development. Crew Dragon spacecraft external shell will accommodate hooks for the tethers possibly near the main hatch. Since there will be no human launches on these Dragons, the Superdraco thrusters may be removed. Also, spin and de-spin thrusters need to be installed, possibly in the service modules of the Dragons. The two Dragons will each be augmented with two thrusters each, one for spin and the other for de-spin. The two thrusters on each Dragon will be placed in 180 degrees of each other.

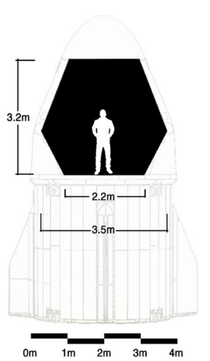


Figure 6: A conceptual section of the dragon module with the interior outfitting removed. Source: Author

Figure 5: Testbed concept. Interior as seen with and without the fittings on the left and right of the image respectively. Source: Author, SpaceX

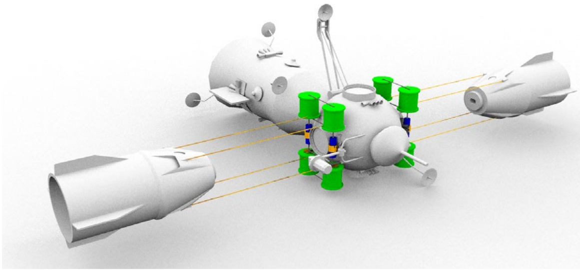


Figure 7: An overview of the testbed highlighting the tether system. Source: Author

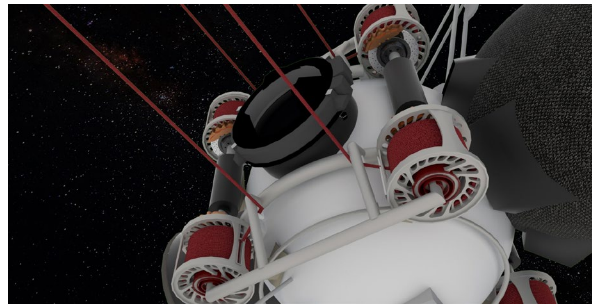


Figure 8: The coil springs located inside the spools are loaded when the Dragons are tethered out. Source: Author

C. The tether system

1. Tether system design

The tether system in design for the testbed needs to embody the following characteristics: independent lengths for the two Dragon modules, compact, light, simple, enable easy retraction and reliable. To comply with these requirements, the tether system design consists of a spool which has a coil spring, a primary braking system and a motor on the axis of the spool as shown in figure 7. The coil spring is loaded when the Dragon modules are tethered out in order to make retrieval easier as seen in figure 8. An automotive disc-brake derived primary braking system controls the flow of tethers and radius of rotation. The motor is powered by batteries of the central hub. The tether system also has two levelling systems: static and dynamic. The static levelling system safeguards the tether in proper position between the Dragon module and tether system. The dynamic levelling system ensures the tether is retrieved and spooled at the proper place and the distribution of the tether on the spool is even. The two levelling systems have an optional secondary braking system in between them which consists of two non-rotating cylindrical surfaces controlled by a dedicated actuator. Figure 9 illustrates a schematic diagram of the tether system. Figure 10 shows a detailed view of the tether system.

The tether system has been derived from the Oedipus-C tether deployer developed by CSA & NASA[7] (shown in figure 11) and the Space Tether Automatic Retrieval (STAR) experiment, credits to DLR & ESA[8] (shown in figure 12). The testbed tether system has two independently variable subsystems allowing two Dragons to be oriented at different distances from the hub to compensate for mass imbalances between the two Dragon modules. Variations in the lengths of the tethers on two sides ensures the center of rotation of the Testbed always to align with the center of the spherical Prichal module.

2. Selection of the rope.

Evaluation criteria for rope and material selection

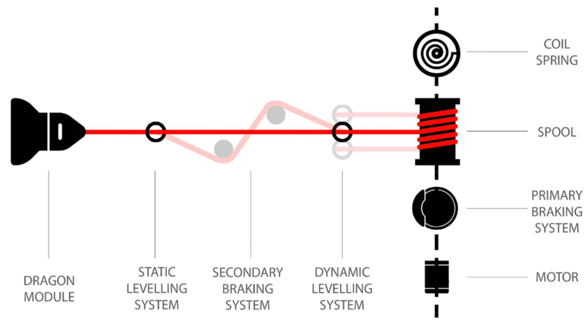


Figure 9: A schematic of the tether system. Source: Author.

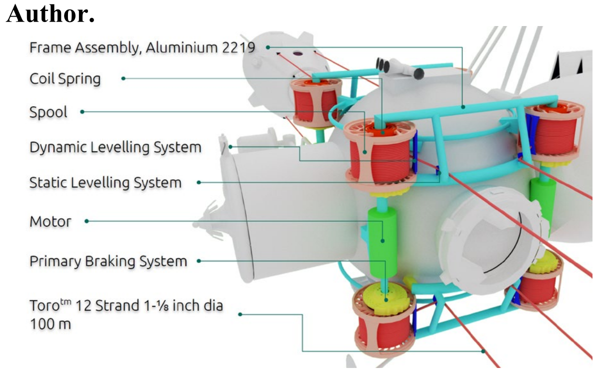


Figure 10: A detailed view of the tether system on the testbed. Source: Author

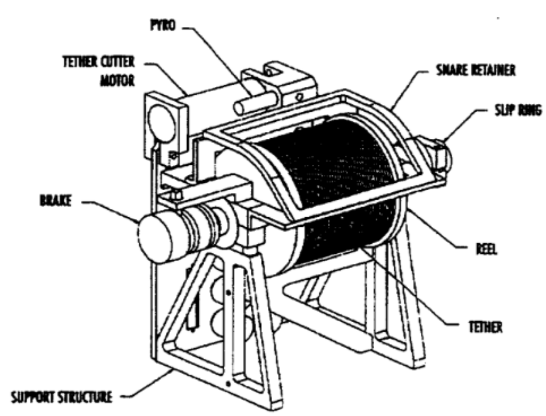


Figure 11: The Oedipus C tether system. Source: Tethers in Space

includes ultimate and yield strength, reliability, heritage, cycling, long-term degradation, issues with long-term exposure to UV/GCR/atomic oxygen in LEO, and electrical conductivity. Two types of ropes were compared and evaluated: Vectran and Toro 12 strand. Vectran has flight heritage but has only limited number of applications and has not been used for heavy deployable tethers before. It has been a tested for space environment exposure as webbing restraint material for inflatable modules, but no post-exposure testing was reported to evaluate material degradation. Vectran can be used for ropes or straps. Toro™ 12 Strand is manufactured from High Modulus Polyethylene (HMPE) and is a wire rope replacement with low stretch, torque-free, superior flex fatigue, and wear resistance, according to the company's tech sheet.

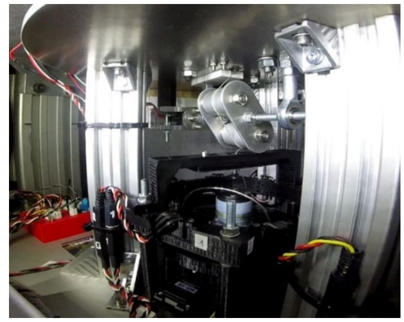


Figure 12. The braking compartment of the STAR tether system. Source: ESA and DLR.

There are four lines of tether on each crew Dragon. Once a tether has lost it's functionality, whether by fatigue/fraying or mechanical failure of the winching mechanism, the load distribution will shift from square to a triangle geometry.

Table 4: Comparison of size and weight of the tether rope options. Source: Author

	Vectran		Toro	
Factor of Safety	size (in)	total tether mass (kg)	size (in)	total tether mass (kg)
5	3/4	166.4	7/8	110
10	1-1/8	274.8	1-1/8	180.4

Figure 13. Toro ™ 12 strand. Source: Cortland

To compensate for the acting load moving off the center, a diametrically opposite tether will be dis-engaged to keep the loads symmetrically distributed. Loads distribution directly affects requirements for the tether and sizing of the mechanism. Table 4 shows metrics for each side of the two independent Testbed tether systems for worst-case scenario when only two ropes remain active. After analyzing two materials, Toro 1-⅛ inch diameter with a factor of safety 10 was selected for tethers due to it's low stretch, torque-free, superior flex fatigue, and wear resistance properties (Figure 13). However, the Toro material has not been tested in flight yet and limited data of it's reaction to UV/GCR/atomic oxygen in space is available. In addition, wrapping the rope inside an amberstrand jacket for electrical conductivity and redundancy may be required.

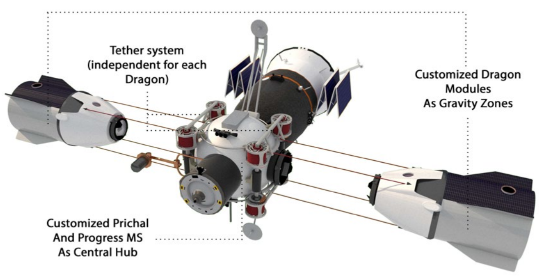


Figure 14. Tbe testbed in free flying mode & Dragons partially tethered out. Source: Author

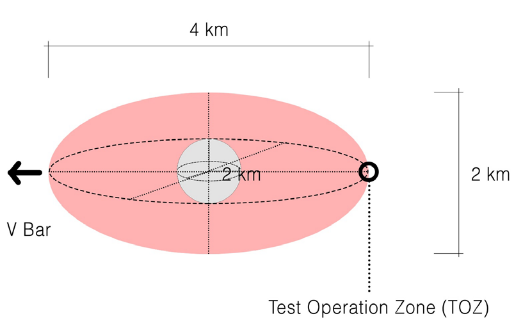


Figure 15. Location of TOZ. Source: Author

D. Definitions

1. Testbed Docked mode

When the Testbed is in docked mode, it's solar arrays will be deployed which would allow the power system to be active to charge the batteries while the ECLSS, Comms and GNC subsystems remain switched off.

2. Testbed free-flying mode

In free-flying mode, the Testbed's solar arrays will be folded and its subsystems activated as shown in figure 14.

3. Test Operation Zone (TOZ)

The TOZ is located 2000 m aft from the center of mass of the ISS. This location has been placed at the edge of the approach ellipsoid. All the experiments will be carried in this zone during Testbed rotation period (Figure 15).

1. Test operations

The Testbed will serve two sets of test objectives: first technical and subsequently physiological test objectives. The "test operations" which serve the technical test objectives are named T1, T2, T3,… that will be carried out sequentially until the subsystems are finetuned and the Testbed is certified as human rated. Next, test operations P1, P2, P3… will be conducted with human test subjects on board. After every test operation, the Testbed will return to the ISS and prepare for the next test operation. Table 5 shows different aspects of selected test operations.

Table 5: Details of test operations. Source: Author

Test Operation ID	Duration of test	Objective of test operation	Radius of spin	Gravity generated	RPM
T0	Move to TOZ: 30 mins Spin up: NA Stay at TOZ: 20 mins Spin down: NA Return to ISS: 30 mins	• "Static test" designed to confirm testbed can retreat to TOZ and return to ISS safely without spinning up.	NA	NA	NA
T1	Move to TOZ: 30 mins Spin up: 20 mins Stay In Spin: 20 mins Spin down: 20 mins Return to ISS: 30 mins	• Development of the following subsystems: ECLSS, GNC, Power, Propulsion and AAC, Spin up and spin down, and Tether. • Refinement of test protocols: docking-undocking and spinup-spindown	10m	1g	9.5
T2	TBD	Same as above	TBD	TBD	TBD
…	…	…	…	…	…
P1	Move to TOZ: 30 mins Spin up: 20 mins Stay In Spin: 20 mins Spin down: 20 mins Return to ISS: 30 mins	Perform short-term physiological tests. In the framework provided by James R. Lackner, Paul DiZio in 1998; Gilles Clément in 2015; and Al Globus, Theodore Hall in 2017.	TBD	TBD	TBD
P2	TBD	Same as above	TBD	TBD	TBD
…	…	…	…	…	…

E. ConOps

The figures 16 to 30 show the launch sequence of the different components of the Testbed, their in-orbit integration and a generic test operation. The figure 31 shows the ConOps for the test operation T1 as a functional flow block diagram of the sequence of events for executing the test operation. Similarly T2, T3, …, P1, P2, P3, … will have ConOps nearly identical to T1 with only changes in time durations.

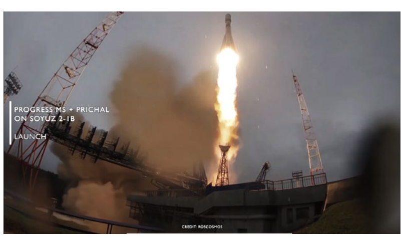


Figure 16: The central hub is launched on a Soyuz 21-b. Credit: Roscosmos

Figure 17: The central hub docks to the Zvezda module of the ISS. Source: Author

Figure 18: Customized dragon module 1 is launched on a Falcon 9. Credit: SpaceX & NASA

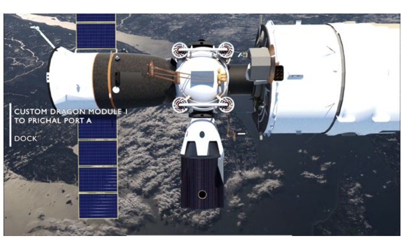


Figure 19: Customized dragon module 1docks to the central hub. Source: Author

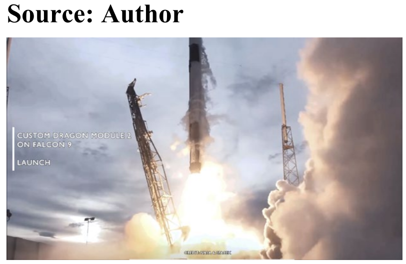


Figure 20: Customized dragon module 2 is launched on a Falcon 9. Credit: SpaceX & NASA

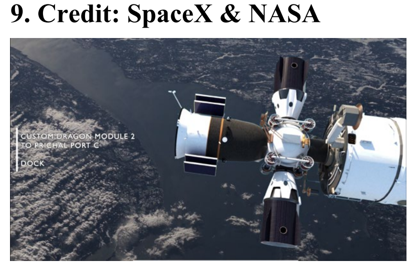


Figure 21: Customized dragon module 2 docks to the central hub. Source: Author

Figure 22: EVA to hook tethers up. Credit: NASA

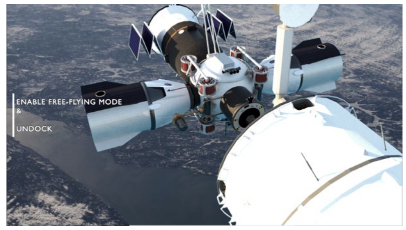


Figure 23: Testbed switch to free flying mode and undocks. Source: Author

Figure 24: Testbed parks and TOZ and starts spin-up protocols. Source: Author

Figure 25: Testbed remains in spin for duration of experiment. Source: Author

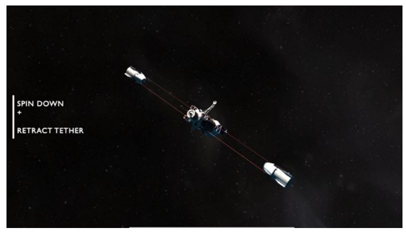


Figure 26: Testbed spins down and retracts tethers simultaneously. Source: Author

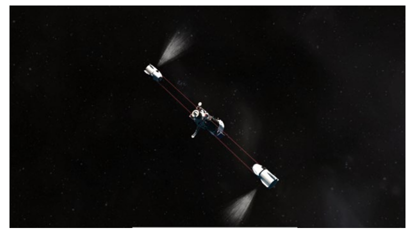


Figure 27: The spin-down thrusters being fired to slow the spin of the testbed. Source: Author

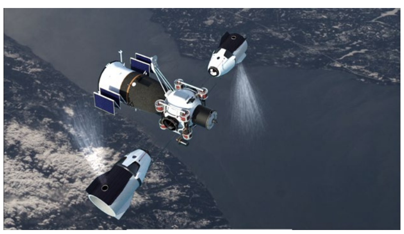


Figure 28: The spin-down thrusters being fired to kill the roll of the testbed. Source: Author

Figure 29: The Dragon modules dock to central hub and retreats back to the ISS. Source: Author.

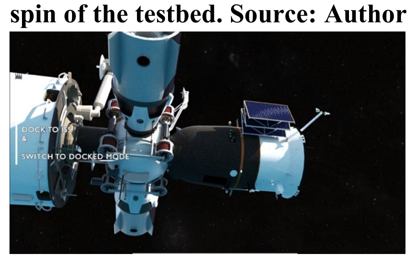


Figure 30: The testbed docks back to the ISS and switches to docked mode. Source: Author.

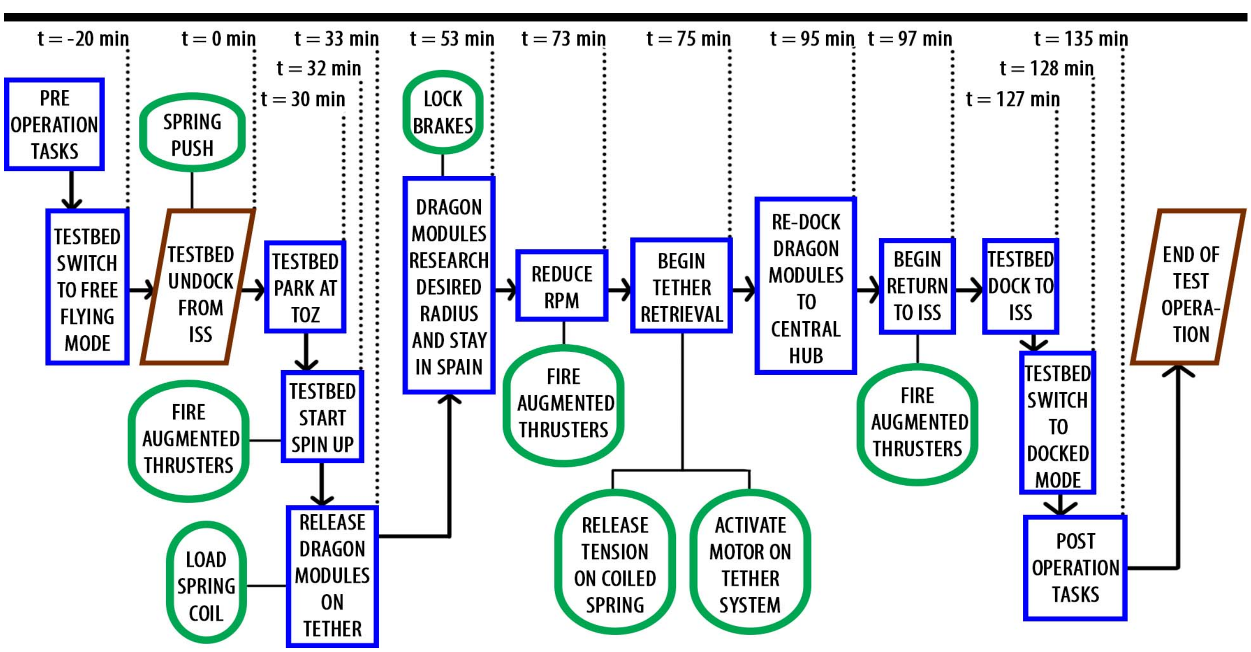


Figure 31. Functional Flow Block Diagram of ConOps of test operation T1. Source: Author

X. Assumptions

Some assumptions had to be made for development of this project., For example, in-orbit refueling capability is required for Testbed operations to maintain feasibility of it's operations and expand its lifecycle. Next assumption is that the power generated and stored while in the docked mode has to sustain the duration of the longest test operation. And lastly, costs of Prichal, Progress, development and maintenance were estimated to the best of the authors' knowledge.

XI. Risks and Mitigations

Table 6: Identification of the risks and their respective mitigations. Source: Author

Risk	Mitigation
Static discharge is a possibility when the two Dragon modules come back to dock to the central hub.	Use of conducting tethers
Center of Gravity offset from the center of the central hub	Adjust tether length independently on the two Dragon modules
Use of hypergolic fuels	Adoption of thrusters which utilize safer fuel mixtures
On-orbit iteration of technical systems might be challenging	Iterate technical systems from ground before launch
Low Clearance to Zvezda	Collar / extension on the port connecting Zvezda to Prichal

XII. Calculations

Table 7 shows mass and cost calculations of the Testbed. All costs are shown in million USD. The values marked with asterisks are the author's estimation.

Table 7: Identification of the risks and their respective mitigations. Source: Author

<table>
<tr><th>ID</th><th colspan="2">Element</th><th>Cost (million)</th><th>Quantity</th><th>Total cost (million)</th><th>Mass (kg)</th></tr>
<tr><td>1</td><td colspan="2">Crew Dragon</td><td>$310</td><td>2</td><td>$620</td><td>24000</td></tr>
<tr><td>2</td><td colspan="2">Prichal (UM) module</td><td>$200*</td><td>1</td><td>$200*</td><td>4000</td></tr>
<tr><td>3</td><td colspan="2">Progress MS</td><td>$300*</td><td>1</td><td>$300*</td><td>3290</td></tr>
<tr><td>4</td><td rowspan="2">Launch</td><td>Soyuz 2-1b (UM + Progress)</td><td>$80</td><td>1</td><td>$80</td><td rowspan="4">-NA-</td></tr>
<tr><td>5</td><td>Falcon 9 (Crew Dragon)</td><td>$62</td><td>2</td><td>$124</td></tr>
<tr><td>6</td><td colspan="2">Development</td><td>-NA-</td><td>-NA-</td><td>$100*</td></tr>
<tr><td>7</td><td colspan="2">Maintenance / Ground support</td><td>-NA-</td><td>-NA-</td><td>$100*</td></tr>
<tr><td>8</td><td colspan="4">Grand Total</td><td>$1524</td><td>31290</td></tr>
</table>

Taking T1 as an example with a spin radius of 10m, RPM of 9.5, and spinning period of 20 mins, a projected scenario assumes thrust that is throttled up linearly from 0 to 257N over a period of 20 mins as shown in figure 32. It is important to remember that the radius of spin is also linearly increasing from 0 to 10 m in the same time period. In such a case, the g-dose curve, as shown in figure 33, follows a power curve as: $y = axc+b$. It is not clear how humans on board will react to such conditions and only actual experiment can answer that question. Functionality of technical systems in g-curves will have to be investigated as well.

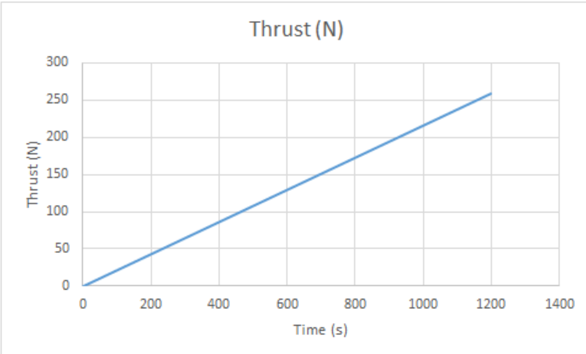


Figure 32: The thrust profile in a sample test experiment. Source: Author

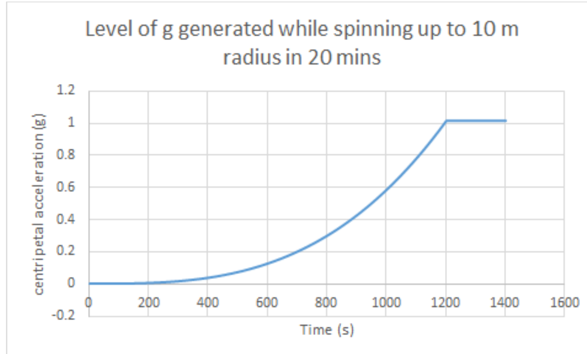


Figure 33: The g-dose profile in the sample test experiment. Source: Author

Since the mass of the Testbed is estimated to be 31 metric tons, we can calculate the forces required for its spinning (figure 34). On the x-axis is the radius of the spin condition in meters and on the y-axis is the amount of thrust required to reach the specific spin condition in Newtons. The calculations were done for generating 1g in various ways. Radius and time to spin-up the Testbed were two variable parameters.

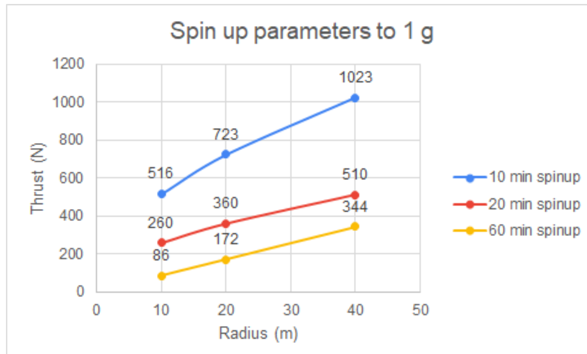


Figure 34: Chart showing the amounts of thrust required to attain various spin conditions. Source: Author

For calculating fuel reiurements, we assumed that the KDTU-80 thrusters utilized on the Progress along with similarly sized tanks are introduced to the service module of Dragons allowing to calculate how much fuel will be required to support all operations. These calculations do not include the thrust needed to go to-and-from the TOZ and are only for fueling spinning up and spinning down operations that can be included in the future work.

The dt of the KDTU-80 set up on the Progress is 890 seconds, I_{sp} is 302 seconds, the maximum thrust is 2950 N. Tthe fuel capacity of the Progress is estimated as,

$$d_m = (F \times dt) / I_{sp} \times g_0 \qquad (1)$$
$$= (2950 \times 890) / 302 \times 9.81 = 886 \text{ kg.}$$

For the augmented thrusters on the Dragon modules, without considering time for the spin-up or spin down, fuel mass spent to spin up to the radius of 40 m is,

$$dm_a = (F \times dt) / I_{sp} \times g_0 \qquad (2)$$
$$= (500 \times 600) / 302 \times 9.81 = \sim 100 \text{ kg.}$$

Therefore, if 100 kg of fuel spent during spin-up and another 100 kg for spin-down, with the same sized tanks and same specs, **possible number of test operations before refueling will be: 886 / (100 x 2) = ~5.**

For the augmented thrusters on the Dragon modules, without considering time for spin-up or spin down, fuel mass spent to spin up to the radius of 10 m is:

$$dm_a = (F \times dt) / I_{sp} \times g_0 \qquad (3)$$
$$= (43 \times 3600) / 302 \times 9.81 = \sim 50 \text{ kg.}$$

Therefore, 50 kg of fuel spent during spin-up and another 50 kg for spin-down, with the same sized tanks and same specs, **possible number of test operations before refueling will be: 886 / (50 x 2) = ~9.**

XIII. Path Forward

There are multiple avenues for taking this project forward. More detailed calculations need to be done on the forces acting on the testbed while spinning up and spinning down. That will lead to a better understanding of fuel requirements for test operations. The tether system also requires further research. A small satellite testbed for the tether system can help to develop and flight prove the tether system before the Testbed launches. An interface diagram to identify interdependencies with the ISS while in a docked position will be needed to understand power and other requirements. Dragon modules have pre-integrated systems for microgravity and Earth gravity conditions. However, subsystems for partial gravity and rotating environment may need to be developed. Also, the interior architectures of the central hub and Dragon modules need to be designed.

XIV. Conclusion

This paper presents a proposal to address a knowledge gap in understanding long term effects of partial gravity on engineering systems, human physiology and psychology. The proposed platform is a bridge which connects the current state of Earth -based human centrifuges and limited animal testing in partial gravity in orbit to the future state of long- term human habitats and colonies on Mars and beyond. Leraning if long term exposure to partial gravity conditions degrades human health allows to develop mitigation strategies prior to deep space travel to Mars and beyond. The estimated cost of $1.5 billion is around 7% of NASA's budget for the fiscal year 2019. It is also 40% the cost of the Nautilus-X spacecraft[9]. Even though this is a relative comparison since the Nautilus-X intended to be a DST vehicle, it still highlights that $1.5 billion is a feasible amount for a project that can potentially revolutionize deep space exploration.

In addtion, the proposed research platform may provide multiple "spin-offs" or inspired projects. This variable gravity platform in LEO may serve as TRL testing laboratories for partial gravity environments offering relatively easy access from and to Earth. It could also enable long term human habitation in LEO, a space port with hotels and rehabilitation centers where sustained partial gravity / hypergravity is utilized to fight obesity and aging 1, fuel depots, etc. However, to reach these future potentials, deep space missions-associated challenges need to be identified that can be mitigated and solved by AG utilization.

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The completion of this undertaking would not have been possible without the feedback and assistance of Prof. Larry Bell, Mr. Kriss Kennedy, the support of Mr. Larry Toups from the Sasakawa International Center for Space Architecture (SICSA). We would also like to express our deep appreciation to Spencer Stanford for the discussions, Victor Kitmayen for sharing his research and references to get me started, Vittorio Netti and Joanne Vaiphei for providing crucial feedback and ideas, and last but not the least, Rahul Venkataraman, Justin Lin and Timothy Bishop for helping me quantify the features and cycles. Les Johnson, Justin W. Rowe, and Amandarose Kiger, we thank you for your inputs on the tether system.

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