50th International Conference on Environmental Systems
12-15 July 2021
ICES-2021-318

A Strategic Pathway to the Artificial Gravity Testbed Element in Low Earth Orbit

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This paper is a continuation of previous investigations of a testbed for an artificial gravity (AG) platform in low Earth orbit. The goal of the initial design proposal is to address a knowledge gap in our understanding of the long-term effects of partial gravity on physiological and psychological human capabilities. Therefore, the objective is to create a capability to undertake research to address this knowledge gap. Because human centrifuges on Earth cannot recreate effects of partial gravity on human physiology and parabolic flights fail to provide long enough exposures to generate reliable data, novel research platforms to investigate partial gravity effects on humans and systems are needed. The proposed artificial gravity 3-body testbed (AG Testbed Element) will comprise two customized crewed-Dragons docked to a Central Hub, which in turn will dock to the Zvezda module of the International Space Station intermittently. The goals & objectives of the AG Testbed have been divided into two categories: technical and physiological. The testbed's first phase will develop the technical systems to ensure the spinning testbed is human rated. The second phase will be dedicated to physiological research test objectives. First, this paper explores the AG Testbed Element Design, Development, Test & Evaluation (DDT&E) plan and risk mitigation strategies. Secondly, this effort explores an evolutionary roadmap towards a larger, more robust platform which will address the knowledge gap mentioned later. It takes a critical look at how the AG Testbed Element will play an important role in the commercialization of space in LEO. The combination of these two paths of exploration culminates with a strategic vision and development plan for investors and stakeholders. The AG Testbed Element and subsequent research will expedite the tipping point of artificial gravity research.

Nomenclature

LEO	=	Low Earth Orbit
R&D	=	Research and Development
WBS	=	Work Breakdown Structure
VGLSF	=	Variable Gravity Life Sciences Facility
AGSEV	=	Artificial Gravity Space Excursion Vehicle
SICSA	=	Sasakawa International Center for Space Architecture
SWOT	=	Strength, Weakness, Opportunity, and Threat
ConOps	=	Concept of Operations
COTS	=	Commercial Off The Shelf
SLS	=	Space Launch System
CAD	=	Computer Aided Design
VR	=	Virtual Reality
AR	=	Augmented Reality
MR	=	Mixed Reality
AG	=	Artificial Gravity
PRA	=	Probabilistic Risk Assessment
DDT&E	=	Design, Development, Testing, and Evaluation

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I. Introduction

THERE is a knowledge gap in our understanding of the human body's adaptation to spinning or rotating environments in microgravity and spinning environments in general (Clement, 2015). Lackner and DiZio (1998) have presented their findings regarding adaptation in a rotating artificial gravity environment. Globus and Hall (2017) have also studied the rotation tolerance of humans, compiling multiple previous experiments, and presenting their own combined chart representing the comfort zones considering rotation rate and radius of spin as two interdependent variables. For all the valuable data they have produced, these experiments were all limited as the Earth's gravity vector contaminates experimental conditions, they had to limit the time of the experiments and they all had a relatively low radius of spin since they were all situated on the Earth's surface. If we are to truly understand the effects of spinning environments on humans, and consequently effects of partial gravity on the human physiology and psychology, we need to take our artificial gravity labs to LEO where the limitations mentioned earlier can be mitigated. How we do it in a strategic manner is the subject of this investigation.

Artificial gravity has generally been proposed as a mitigation strategy to address the negative effects of prolonged crew-exposure to micro-gravity conditions during long space flights (Clement, 2015). With this paper, we are investigating another aspect of artificial gravity usage; to address the knowledge gap regarding the effects of prolonged exposures to partial gravity on the human body and mind. It is essential that this knowledge gap is addressed before we send humans out for long term, deep space missions to the Moon, and especially Mars.

The proposed 3-body testbed comprises two customized crewed Dragon capsules docked to a Central Hub, which in turn docks to the Zvezda module of the International Space Station as seen in the Figure 1 (Rajkumar and Bannova, 2020). A critical component of this testbed is the tether system shown in Figure 2. The testbed is a result of a phased approach towards assembly of a Variable Gravity Research platform in LEO, which will address the knowledge gap mentioned earlier. After Earth based centrifuges, the next step in this phased approach is the Testbed for the Variable Gravity Research Platform in LEO which will test out the hardware and build confidence prior to putting humans in rotating structures in space for short periods of time at a low cost. The next step would be the Variable Gravity Research Platform in LEO itself which would allow for long term experiments. It will allow not only to test for adaptations to rotating environments but research effects of exposure to long periods of partial gravity conditions in preparation for future Lunar and Mars missions.

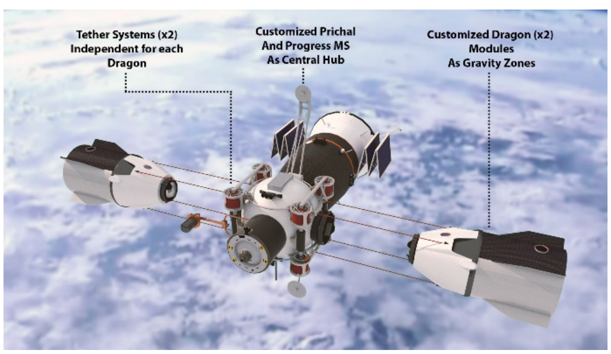

Figure 1. Basic components of the testbed.
Source: Authors

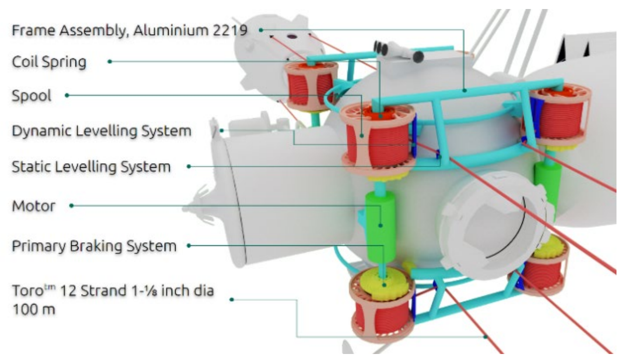

Figure 2. Conceptual Tether System
Source: Authors

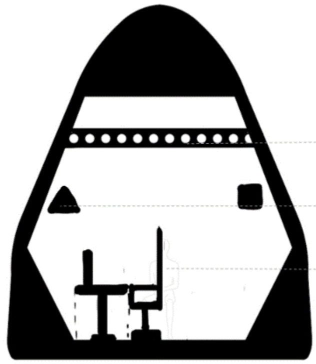

Figure 3. Sketch of one of the possible interior configurations of the crew dragons.
Source: Authors

The testbed itself is designed to capitalize on pre-existing capabilities of the ISS and commercialization of LEO. To minimize time for R&D, we are proposing to use off-the-shelf technologies as much as possible including Crewed Dragons, Progress MS, and the Prichal module. There has also been an investigation into the interior design of the crew dragons and a preliminary identification of the human experiments to be performed inside it as shown in Figure 3 (Rajkumar and Bannova, 2020).

The design methodology followed during the development of the project is captured here in Figure 4. It started off with identification of the issue, which was the knowledge gap on the long-term effects of partial gravity on human physiology and psychology. Then, the vision, mission, goals, and objectives were identified to address this issue. The next phase was to identify the scope of the research, detailing out which aspects of the research are to be focused on (such as mission planning, Concept of Operations, etc.) and which parts would remain out of scope (such as detailed design of subsystems). Keeping this in mind, the next phase was to develop a work plan where the timeline of the research was blocked out according to work breakdown structures (WBSs). Subsequently, the first real foray into hard research on the topic in hand was to understand the basics of artificial gravity and the different ways it could be generated.

Apart from the common spinning/rotating strategy of generating artificial/partial gravity, other alternate strategies were considered, such as constant linear acceleration, suborbital hops, eccentric orbital spacecrafts, suspension from balloons, underwater operations, and so on. However, it soon became apparent that the common method of spinning/rotation was the most suitable for application in this case. Studies were conducted on precedent research and projects on generating artificial gravity. Two student projects which were published by the Sasakawa International Center for Space Architecture, the Variable Gravity Life Sciences Facility (VGLSF) and the Artificial Gravity Space Exploration Vehicle (AGSEV) became crucial to the case studies (SICSA, 1988). Afterwards, a strength, weakness, opportunities, and threats (SWOT) analysis was performed on precedent case studies which helped inform the preliminary design concept (Rajkumar, 2019). Another SWOT analysis was conducted on the preliminary concept at this stage which helped estimate the direction of future research (Rajkumar, 2019). The next step was to refine the timeline of events according to this newfound understanding. Test objectives were identified which informed the development of the concept of operations which in turn helped derive the functional requirements of the testbed.

Next, trade studies were conducted to decide which assets/products available on the market would best suit the central hub and the space vehicle modules of the testbed. Then, the tether system concept was developed and calculations on the time of spin up/spin down, assumed fuel capacity, number of spin up/spin down bursts possible, etc. were performed to check the feasibility of the design. The next step of the process was to identify preliminary risks to the system and their possible mitigations, identify opportunities to make the testbed better/apply it in related fields like a deep space transit vehicle. Through formal and informal peer review presentations, feedback was captured from the NASA community of experts in the discipline areas of human systems integration, human factors and habitability, and space architecture, which informed refinement of the conceptual design. The refined design was documented in various technical papers for conferences which led to identification of the path forward.

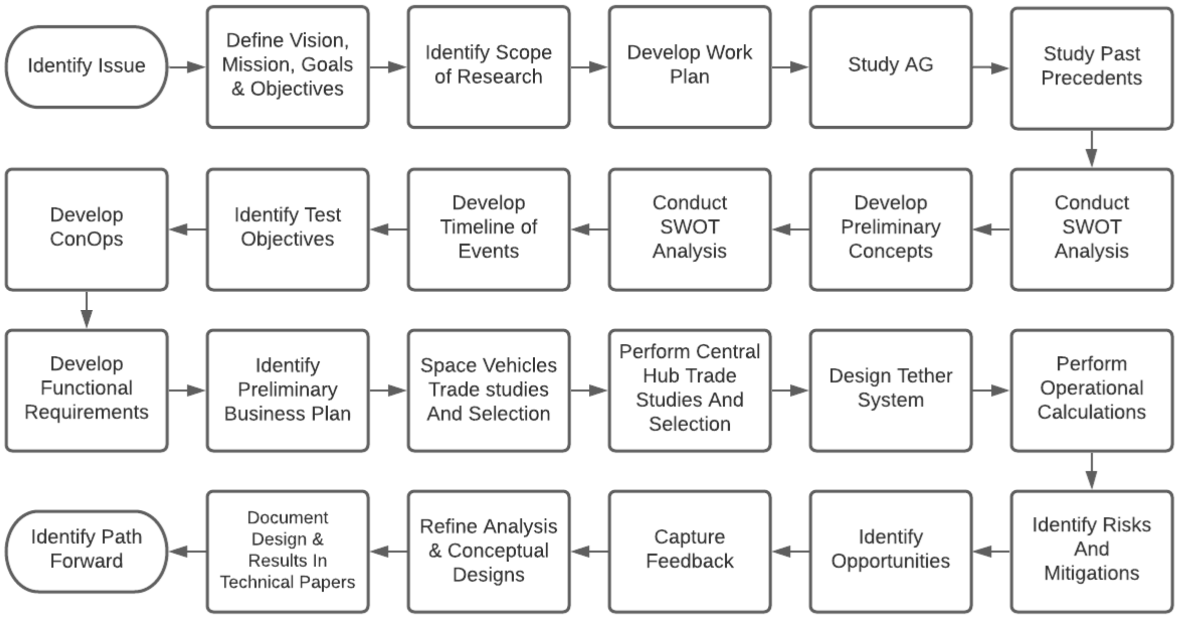

Figure 4. Design methodology.
Source: Authors

II. Design, Development, Testing, & Evaluation (DDT&E) Plan

To take forward the research conducted so far, this paper explores in depth, the design, development, testing, and evaluation strategies developed; and expands on the risk mitigation strategies preliminarily identified earlier in the process.

A. Design and Development Plan

The three primary efforts to consider when developing the design and development plan for the testbed are the design definition, the trade studies identification, and because of these two, how the development plan shapes up. Although the testbed has been developed based on preliminary design criteria, it is important to reevaluate the design considering the more formalized design and development plan put forward in this paper.

1. Design Definition

As part of the design definition, we have looked at design criteria, functional definitions, and ConOps definitions. The latter two are out of scope of this paper and have been discussed in previous papers (Rajkumar, Bannova 2019). The design criteria have been adopted from a white paper on Habitat Design Criteria (Kennedy, unpublished) and have been classified into various categories: Programmatic, Human System integration, Operations and Training, Engineering, and Manufacturing and Assembly. The criteria themselves can be more optimized for the testbed in the future. The testbed must be re-examined in this framework to refine its design. The importance of these habitat design criteria is to understand all the implications and design drivers on the system being developed. A concurrent engineering and systems architecting approach is used to ensure all criteria are considered during the design and development process.

1.1 Programmatic
1) Constraints – Technical risk, Cost, Schedule, Mass.
2) Longevity – Upgradability, Extensibility/Refueling capability, Robustness, Maintainability.
3) Strategy – Mission objectives, Political alignment, Integration with ISS, Stakeholder agreements.

1.2 Human systems integration
1) Behavioral health - Spatial Organization, Wayfinding, Experience.
2) Ergonomics - Accessibility, Anthropometry, Injury Mitigation, Usability.
3) Interaction between crew and testbed - Object Management, Ease of Learning, Knowledge Capture.

1.3 Operations and training
1) Ground crew - Mission Operations Support, Situational Awareness.

2) On orbit crew activities – Task performance, Workstation use, Autonomy

1.4 Engineering

1) Design margins – LEO environ, Reliability, Reusability, Technology Readiness Level / COTS, Materiality.
2) Levels of testing - Validation of Components, Assemblies, and Subsystems, Integrated Testing.
3) Systems design - Functional Allocation, Design Integration, Ease of Modification, IVA Support for External Tether System, Minimized Secondary Structure, Stowage Design, Modularity.
4) Sustainability - Preventative Maintenance, Longevity, Repairability, Automation, Commonality.

1.5 Manufacturing and assembly

1) Element manufacturing - Production, Assembly, Integration, Manufacturing Techniques, Schedule.
2) Ground Processing - Pre-Launch Integration, Cargo Loading, Activation through Closeout.
3) On orbit internal integration - Deployment, In-Situ Assembly.

2. Trade Studies Identification

Having identified the design criteria, the next step is to make design decisions which satisfy these design criteria. These trade studies serve to support the rationale of choices and help determine how to make intelligent decisions about design, ranging from subsystems scale to mission architecture. They help establish a series of decisions that need to be made to arrive at the testbed in proposal. Some of these testbed studies help to arrive at numerical data to analyze or assess the testbed. The various trade studies have been classified into the same categories as the design criteria. Under each category is listed the name of the trade study and alongside it, the various options to consider and weigh. It is important to note that with selection of Commercial off-the-shelf (COTS) components, multiple trade studies became redundant.

2.1 Programmatic

1) Asset's condition – Repurposed modules in-orbit vs newly launched
2) Independence – Fully dependent on ISS vs Semi-dependent vs fully independent
3) Length of missions – long vs short
4) Launch Vehicle Selection – SLS vs New Glenn vs Starship vs Falcon9 vs Arianne vs others
5 Geometry of structure – Cylinder vs torus vs others
6) Radius of Spin – Low (<10m) vs Medium (10m>r>100m) vs High (>100m)
7) Central Hub Selection – Crew Dragon vs Starliner vs others
8) Connection with ISS – Zvezda module vs others

2.2 Human Systems Integration

1) Human occupation – Permanent human presence vs intermittent human presence on the testbed

2.3 Operations and Training

1) Spin Cycle – Constantly spinning vs intermittently spinning
2) Integration – Integrated on launch vs integrated on-orbit

2.4 Engineering

1) Number of bodies on testbed – 2 bodies vs 3 bodies
2) Use of counterweight – With vs without
3) Power generation – Solar vs Nuclear vs Chemical
4) Power storage – Batteries vs Flywheel
5) Tether selection – Vectran vs Toro vs others
6) Tether system design – Number of tethers, independent vs linked on the two space vehicles, spool stabilizer
7) Docking system – Androgynous vs Non-androgynous,

2.5 Manufacturing and assembly

1) Structure of connection between spinning bodies – Rigid vs deployable, truss vs tether, telescopic vs inflatable, pressurized vs unpressurized
2) Structure of the pressure vessels – Rigid vs inflatable

3. AG Testbed Development Plan

This section is a culmination of the design definitions and the trade studies identified to articulate those design decisions. It investigates how we can incorporate and integrate the various subsystems and ConOps identified so far and how it informs the design. A qualitative analysis can be incorporated during the design and development process as a benchmark for checking if the development is proceeding in a satisfactory manner or not. In the design phase, we can check for attributes such as productivity and innovation (method TBD). In the planning phase, we can check for efficiency in time management. In the manufacturing phase, attributes such as quality of work and budget variance can be taken into consideration. During the testing phase, we can monitor proper test protocols and well was schedule variance. During the assembly / launch phase, we can check for proper data gathering. During the maintenance phase, we can check for quality of maintenance, cost efficiency of the maintenance. Finally, during the final phase of disposal, we can check for proper deconstruction/ destruction / repurposing of the testbed. This development plan which has been built on the previous steps enables us to further mature the testbed design and leads to a test and evaluation plan.

B. Test and Evaluation Plan

So far, we have looked at how we develop and integrate the hardware, software, and humans with 3D modeling of the systems. The test and evaluation plan is established to address the hardware + software + human interdependencies related to the development of the testbed. As part of the test and evaluation plan, it is important to include the human as a "system" of the triad of hardware, software, and human. Human System Integration assesses each phase of design, develop, test, and evaluations, as well as life cycle of the systems design, manufacturing, assembly, operations, and disposal of the testbed. Too often engineering focuses only on the hardware and software.

Test objectives relating to technical systems, vehicle performance and capability have been developed for the three phases of the test and evaluation plan, i.e. Simulation modelling, ground testing and orbital testing. These are done in preparation for certification / human rating the testbed. These test objectives are not exhaustive and more can be added as deemed necessary during the development of this project. The test objectives for the simulation modeling of the testbed include understanding the interdependences and interfaces between all the parts, components, subsystems, and systems of the testbed. The test objectives for ground testing include understanding the performance of the parts, components, subsystems, and systems to ensure they meet the functional and performance requirements. Finally, the test objectives of orbital testing include understanding overall system performance, operations, and verification that the system is ready for human occupancy and human testing.

1. Simulation Modelling

In this phase, we will model and run simulations of the entire system's design, functions, and performance of the testbed. This modeling and simulation will be used to characterize and understand the interdependencies between the *parts, components, subsystems, and systems.* The simulations will also be used to validate the Concept of Operations of the testbed. Simulation modeling is an important first step in understanding all the inputs and outputs between all the part and components of the system. The purpose of model validation is to develop objective evidence that will be used to analyze the systems and products of the testbed to reflect the real world as accurately as needed to simulate the system performance. Simulation models can be used as a "digital twin" of the built flight system to run trouble-shooting diagnostics. Simulation models can also become the foundational work of the software linking functional and performance requirements. Simulation "runs" will study the interaction and interfaces between systems of the testbed, such as the tether system and the propulsion system for example and study the failures modes and affects. Once the model is complete, we will introduce failures in subsystems like power distribution units and determine how we can mitigate/ resolve the failure. For instance, if power is lost on one line-Channel-A, assessments will be performed on how to reroute around this failure.

System Modelling Language (SysML) will be used to model the testbed. It will be used to help identify functions and interfaces of components subsystems, and systems, define performance parameters, and assess overall system operations of the testbed. Using the SysML tool, we can model the entire testbed system to look at performance of subsystems, and their interdependencies. Using a functional bubble diagram, these interdependencies can be visualized and used to drive out and understand requirements like power, and thermal profiles can be assessed. Additional structural modeling will be used for stress detection in the system to understand the failure points, specifically in the crew dragon and the tether system. The dynamic mass distribution/ tether length correction system designed to keep the center of mass/spin in the middle of the central hub is another aspect which will benefit greatly from this modelling. This is also a critical phase for testing out the operating system/ software component of the testbed. We can also define software functions and operating parameters in this phase. Additionally, CAD modelling and Physical modelling will enable human in the loop testing. New technologies like VR / AR / MR can be incorporated into this process to reduce the time and cost of building physical mockups in the early stages. It will enable a faster return time to refine the design from the early evaluation process.

As hardware and software is manufactured and brought together for ground testing, the simulation models are expected to be updated to reflect the as-built performance of these parts and components. The model and simulation will be run again and again to validate the Concept of Operations and assess the verification of the requirements.

2. *Ground Testing*

In the ground test phase, the functional and performance tests will be carried out on benchtops for the engineering and qualification units, which are comprised of the AG testbed components, subsystems, and system. A System Integration Test Lab will be used to start blending the simulation modeling with the manufactured hardware and software. Engineering and qualification units will be used during this phase to stress the hardware and software to push these units beyond the design specification and operating ranges. These tests and their body of evidence will be used later to show compliance with and verification of the requirements. There are several ground tests that will be used beyond the benchtop tests. Test such as the Tether System stresses and operations, Crew Dragon tether attach points stress, spin control, AG testbed internal architecture of the Crew Dragon, and Operational Command & Control, among other tests.

Two identical and customized crew Dragons will be acquired for use in the system. These two crewed Dragons will have most of the interior outfitting removed to make space for the on-orbit artificial gravity research lab. Since there will be no humans launched in it, we can take out the seats, monitors, and the Super Draco launch abort system among other subsystems. Test mannequins will be instrumented to determine the physical forces on human prior to artificial gravity research human testing. A thruster augmentation to the service module will have to be made which will enable the testbed in orbit to spin and de-spin. Qualification tests will also be carried out with a mid-fidelity mockup as qualification units to test if the units meet specifications and will be tested to failure. This is especially applicable for a spin-test of the testbed mid/high-fidelity mockup. Instead of the tethers, trusses can be used for separation of the components in this test to simplify the test. In a separate test for the tether system, it can be tested with dead weights which simulate the weight of the central hub and the crewed Dragons first. Later this tether system can be integrated into the Testbed system and a ground test performed which consists of the tether deployment and retraction test as well as the spin and de-spin test. It is important to point out that initially, this test will focus on testing how the system is spun up and spun down and will not go into dynamics of a system where there are live load shifts. These ground tests can be performed with a Ground Test Facility shown in Figure 6 (right). There is precedence for such a facility in the Lunar Landing Research Facility shown in Figure 5 (left). The ground testing can be done initially with telescoping trusses to control the radius of spin while being supported by a central foundation from below. Additionally, the Crewed Dragons can be supported by trusses on rollers and indicated in the conceptual facility as shown in Figure 6 (right). Later phases of the test can be performed with the Testbed suspended from above and tether system integrated.

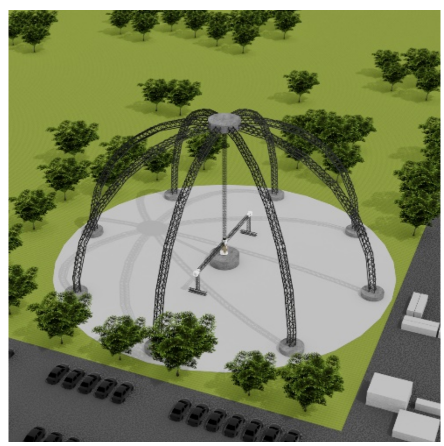

Figure 5. (Left)The Lunar landing research facility with the cranes supporting the lander can be modified to execute ground test for the testbed.

Source: Wikipedia

Figure 6. (Right) Conceptual Ground Testing Facility for the Testbed.

Source: Authors

3. *Orbital Testing*

The orbital test phase will operationally test the flight hardware and software in an uncrewed test prior to allowing a crewed mission. To reduce the cost of the program, one possibility under consideration is the use of Protoflight units rather than qualification units. Since the Crew Dragons are already a human-rated system, with some modifications, it makes sense to "Protoflight" them. The Central Hub and Tether system will have to be assessed whether to use qualification units for the Orbital test or Protoflight units. A risk analysis will need to be performed to assess which way to proceed. The two Crew Dragons, the central hub, as well as the tether system (to a lesser likelihood) may be used in the ground test as well as the orbital test phase. This orbital test vehicle will also undertake the role of the Phase 1 (uncrewed phase) of the testbed, as described in the introduction section, where it will be used to develop the technical systems of a spinning spacecraft in orbit and thus not be human rated yet. Depending on the success of this technical Protoflight testbed in orbit, we can then determine if a separate, more refined testbed needs to be launched either for continuing the technical test objectives or moving onto the physiological test objectives with the human-rated version of the testbed. After the orbital test, we will have the objective data and evidence to prepare for certification of human missions to use it as a testbed for an artificial gravity research platform. To make it human-rated, we must consider a risk-based decision-making process as described in the next section. A risk assessment is performed to analyze where the risks are and put in controls to mitigate the risks identified.

III. Risk Identification and Mitigation

An aspect of the development process is a risk-based decision-making process where we identify risks and mitigations, looking at the highest risks to lowest and addressing them in that order. In addition, this section supports the decision making and planning process. This section identifies the strategy to be followed for risk identification and mitigation for the testbed. A detailed risk identification and mitigation matrix is slated for the future, but a preliminary risk identification and mitigations have been indicated at the end of this section.

1. Risk Mitigation Process

A Probabilistic Risk Assessment (PRA) method will be used to assess the risks and plan which risks need the most attention. The risk mitigation process is derived from the NASA Technical Risk Management Process. In this, we consider. 1) the probability (likelihood) that the testbed will experience an undesirable event and, 2) the consequences, impact, or severity of the undesired event, were it to occur. Considering the established process, the preliminary hazard analysis (PHA) is intended as an organized, systematic risk-informed decision-making process that proactively identifies, analyzes, plans, tracks, controls, communicates, documents, and manages risk to increase the likelihood of achieving the goals. Strategies for risk management include transferring performance risk, eliminating the risk, reducing the likelihood of undesired events, reducing the negative effects of the risk (i.e., reducing consequence severity), reducing uncertainties if warranted, and accepting some or all the consequences of a particular risk. The tailored analysis process adopted is as follows:

a. Review requirements, concept of operations, mission architecture, elements, and systems design.
b. Perform Preliminary Hazard Analysis (PHA). Review PHA, emergency procedures & safety standards.
c. Perform Risk Analysis to determine risks, likelihoods, and consequences.
d. Define Test Objectives and map to simulations, ground, and orbital testing to mitigate risks.

The NASA risk matrix will be used to assess the importance in addressing the risk. It is a 5x5 matrix with likelihood of occurrence on the vertical axis and the consequence on the horizontal axis as shown in Figure 7. Each tile is given a “risk matrix score” which ranges from 1 to 25. 1 being least risky and 25 being the most. It combines qualitative and semi-quantitative measures of likelihood and similar measures of consequences.

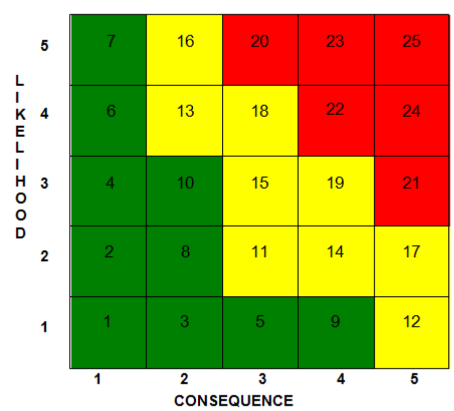

Figure 7. NASA risk matrix classification showing low(green), moderate(yellow) and high(red) importance of risks.
Source: NASA

In accordance with the NASA S3001: Guidelines for Risk Management, the likelihood is given a rating of 1 to 5 as shown in Table 1 below. The score assigned to a particular risk for this research is based on estimations done by the authors.

Table 1. Risk likelihood Criteria.
Source: NASA

Likelihood		
Score	Likelihood of Occurrence (p)	
5	Near certainty	p > 80%
4	Highly likely	60% > p > 80%

3	Likely	40% > p > 60%
2	Low likelihood	20% > p > 40%
1	Not likely	p < 20%

In accordance with the NASA S3001: Guidelines for Risk Management, the consequence is also given a rating of 1 to 5 as shown in Table 2 below. Depending on the nature of risk, the consequences can be either performance, safety, schedule, or cost related.

Table 2. Consequence likelihood Criteria.

Source: NASA

Consequence					
Type \ Rating	1	2	3	4	5
Performance	Minimal consequence to objective / goals	Minor consequence to objective / goals	Unable to achieve a particular objective/goal but remaining objective/goals represent better than minimum success outcome.	Unable to achieve multiple objectives/goals but minimum success can still be achieved or claimed.	Unable to achieve objectives/goals such that minimum success cannot be achieved or claimed.
Safety (Human)	Discomfort or nuisance	First aid event per OSHA criteria	No lost time injury or illness per OSHA criteria	Lost time injury or illness per OSHA criteria	Loss of life
Safety (Asset)	Minimal consequence: asset has no sign of physical damage	Minor consequence: asset has cosmetic damage and is repairable	Minor consequence: asset is damaged but repairable	Major consequence: asset is substantially damaged but repairable	Destroyed: Asset is compromised, and is un-repairable: a total loss
Schedule	Minimal consequence	Critical path is not slipped; total slack of slipped tasks will not impact critical path in less than 10 days	Critical path is not slipped; total slack of slipped tasks is within 10 days of impacting the critical path	Critical path slips	Critical path slips and one or more critical milestones or events cannot be met
Cost	Minimal consequence	Minor cost consequence. Cost variance ≤ 5% of total approved FY baseline	Cost consequence. Cost variance > 5% but ≤ 10% of total approved FY baseline	Cost consequence. Cost variance > 10% but ≤ 15% of total approved FY baseline	Major cost consequence. Cost variance > 15% of total approved baseline

2. *Preliminary Risk and Mitigation Analysis*

In the Table 3 shown below, we have identified some risks and their possible mitigations.

Table 3: Preliminary risk and mitigation analysis.
Source: Authors

ID	Risk	Conse-quence type	Conse-quence Rating	Likeli-hood Rating	Risk Matrix Score	Mitigation
1	Given that static discharge is a possibility when the two Dragon modules come back to dock to the central hub if the tethers are electrical insulators; there is a likelihood that the electrical system on the testbed will suffer shortages.	Perfor-mance	5	5	25	Mitigation strategy is to use of electrically conducting tethers to ensure there is no buildup of an electric static charge differential between the 3 bodies of the testbed.
2	Given that the mass distribution in the 3-body system of the testbed can change with time causing the Center of Gravity to shift away from the center of the central hub; there is a high likelihood that the center of spin and the center of the testbed will not align resulting in a wobbled spin.	Perfor-mance	5	5	25	Mitigation strategy is to adjust tether length independently and autonomously on the two Dragon modules to adjust the center of mass of the overall system. This will ensure the center of spin always coincides with the center of the central hub.
3	Given that majority of current rocket fuels comprise of hypergolic fuels; there is a likelihood that a leak or improper refueling might result in fires / uncontrolled combustion.	Safety (Asset) And (Humans)	5	4	24	Mitigation strategy is adoption of thrusters which utilize safer fuel mixtures / systems which utilize safer fuel mixtures.
4	Given that we are not able to test for subsystems in partial gravity and spinning conditions until we fly it in LEO; there is a likelihood that on-orbit sub-system swaps will be required where revised subsystems might need to be launched and assembled (after disassembling the current subsystem in question).	Perfor-mance	4	3	19	Mitigation strategy is to launch multiple iterations of the subsystems or design the testbed such that the sub systems are easy to be modified / switched out in orbit. How does Starship development make multiple iterations almost simultaneously?
5	Given that the design and ConOps of the testbed requires the two crew dragons to approach the central hub from the port side and starboard side of the ISS; there is a likelihood that the clearance between the crew dragons and the Zvezda module might be less than desirable for safety clearances during the first assembly of the testbed.	Safety (Asset) And (Humans)	5	2	17	Mitigation strategy is to provide a collar / extension on the port connecting Zvezda to Prichal; or consider alternative docking ports such as on the soon-to-be-launched Nauka module.
6	Given the long tether lines wound in the spool and there is going to be	Perfor-mance	5	5	25	Mitigation strategy is to always keep tension on the tethers

	multiple deployments and retractions of the tether; there is a likelihood that the tether spooling system may encounter a cable jam or may slack and cause a jam.					autonomously; additionally, the spooling mechanism has been designed to prevent cable overlap jam inspired from fishing rod spools. In case of jam, design for unjamming protocols.
7	Given that the tethers are in the harsh environment of LEO and they will be deployed and retracted multiple times; there is a low likelihood that the tether might snap/break.	Safety (Asset)	4	2	8	Mitigation strategy is to have 4 tethers on each side of the testbed so that in case one tether snaps, we can voluntarily disengage the diametrically opposite tether to ensure a more stable configuration than having 3 tethers out of 4 operational.
8	Given that the testbed undocks and docks back to the ISS multiple times in its life span; there is a likelihood that it may encounter issues while docking back to the ISS	Perfor-mance	5	2	17	Mitigation strategy is to divide the lifespan of the unmanned and manned operations. The unmanned phase will be used to develop the reliability of the system so that the statistical probability of such a risk is as low as possible (TBD). If such a situation occurs during a manned operation, we can design for emergency protocols like an EVA maneuver to escape the testbed; a de-orbit maneuver to burn up the testbed in the Earth's atmosphere is also a possibility in the worst-case scenario.

3. Likelihood rating rationale

The likelihood ratings assigned to the risks in Table 3 are based on assumptions made by the authors based on rationale associated with the risks. Table 4 below explains the rationale behind these assigned likelihood ratings.

Table 4: Rationale for likelihood rating assignment.

Source: Authors

Risk ID	Assigned likelihood rating	Rationale
1	5	Height of orbit of the testbed (and the ISS) lies inside the ionosphere.
2	5	Change in mass distribution is an inevitability with human occupation of the testbed.
3	4	Refueling in orbit has not yet demonstrated and the technology is in low TRL
4	3	Long term testing for partial gravity on Earth's surface is not possible.
5	2	With recent demonstrations of the automatic docking capability of the crew dragon, the safety margin for docking will have decreased substantially.
6	5	Ground based tether systems often encounter entanglement.
7	2	The tether is chosen with high factors of safety to avoid snapping.
8	2	With recent demonstrations of the automatic docking capability of the crew dragon, the confidence in docking and redocking capabilities has risen.

IV. Evolutionary Roadmap and Strategic Vision

Having developed the DDT&E plan including the risk mitigation strategies, in this section we investigate how the evolutionary roadmap and strategic vision is informed by it. The development of the Testbed has been divided into milestones to guide the development and measure readiness of the testbed. Incremental milestones feed into overall roadmap; a phased development milestone which is enabled by technology milestones as shown in Figure 8 below.

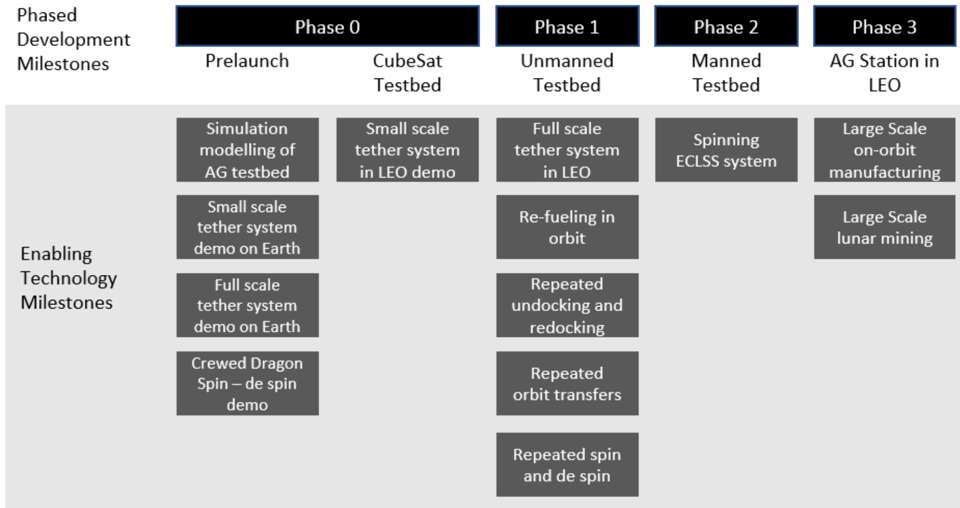

Figure 8. Strategic vision showcasing the enabling technologies needed for various phases of the project.
Source: Authors

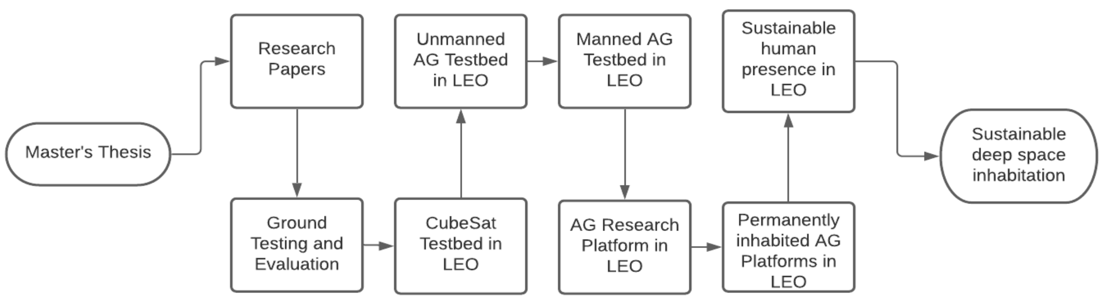

Figure 9. Evolutionary roadmap of the AG Testbed.
Source: Authors

The strategic vision roadmap in Figure 9 above shows how Rajkumar's master's thesis project serves as a foundation for further research to be done in the form of research papers (Rajkumar,2019). This expansion in the research will enable this project to be funded and taken up by parties in higher confidence. Ground testing and evaluation will follow the design and development phase occurring presently. In the ground testing and evaluation phase, as mentioned in the section previous, we will conduct simulation modelling, followed by ground test which is followed by a CubeSat test in LEO which tests a small-scale retractable tether system in LEO as the first portion of the orbital test. The second phase of the orbital test will be the full-scale AG Testbed (also identified as Phase 1 or the Unmanned Testbed earlier. Having this unmanned testbed in orbit and in intermittent docking with the ISS will enable us to develop systems for human occupation of the testbed and human rate it. The crewed portion of the testbed operations can begin where short term adaptations to spinning environment can be tested but more importantly, it will enable the next generation AG facilities to be built which will operate on longer timespans and larger habitable areas to either act as research facilities or commercial space stations like space hotels for tourists. These sustained human presence in AG in LEO will eventually lead to permanently inhabited AG platforms in LEO which will in turn lead to a sustainable human presence in LEO and beyond with off-shoots like AG deep space transit vehicles.

V. Conclusion

The most important aspect of this testbed is that it provides a pragmatic steppingstone towards wide-spread artificial gravity use that we see in visionary narratives of the human space inhabitation. By using off-the-shelf components, this testbed can be put into service in lower development cost and times. In a previous research, the testbed's preliminary feasibility study has been shown for the technical systems (Rajkumar, 2019). This paper has addressed the non-technical aspects and challenges to achieve this goal of building a bridge towards an AG future. A preliminary business plan has been developed to understand the cash and service flows. The investors to this project can be private ventures, private space companies specifically, venture capitalists, federal space agencies, or even philanthropists. The introduction of artificial gravity can be seen as a game changer in our habitation of space. In the short term, this AG testbed can generate revenue by providing a service as an artificial gravity / partial gravity laboratory for research institutes/ universities, government space agencies, or private companies. A private space company could execute this project and offer said services to clients who are interested in flying experiments for lunar gravity or Martian gravity for example. In the long run, this service would be instrumental for companies who are looking to build large scale AG habitat like hotels for space tourism, space ports in LEO etc.

One interesting off-shot from this testbed has been identified to be a deep space AG transit vehicle for Mars transits or beyond. LEO AG facilities like space hotels for tourists are an expected evolution of this testbed too apart from AG research stations in LEO.

An important consideration is to build and maintain momentum to ensure the continued progress of the project. With the impending mass commercialization of LEO, this testbed will be poised to become an enabler for commercialization of research facilities in LEO. Furthermore, additional research needs to be carried out in more detailed calculations on the time-period of operations this testbed can support, a more detailed research on the design and development of the sub-systems and modifications needed on the off-the-shelf components, more detailed interior design of the labs, and a more detailed business plan. Another notable aspect of the proposed testbed is that it is a possible game changer for human inhabitation of space, analogous to how ISRU has been a paradigm shift.

If we are to send humans to Mars and beyond sometime in the future, we need to understand the long-term effects of partial gravity on the human body. And with this testbed, we are bridging this knowledge gap in digestible increments. And this early AG will help bring to life more complicated and grand AG habitats and hence help sustain human presence in space.

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