ILANTHIRAIYAN SIVAGNANAMOORTHY

Student ID - 220197922

EMS690U: Integrated Design Project

A Preliminary Design Study for a Rotating Space Station to Mitigate Microgravity Effects during Long-Term Space Habitation

Contents

1. Introduction

1.1 Project Background & Motivation

Mankind has always sought to explore and extend its presence beyond Earth. The 20th century marked significant advancements, with milestones such as the Apollo Moon landings and the development of the International Space Station (ISS) and today, these ambitions have grown to include permanent lunar bases and crewed missions to Mars (Wu et al., 2012; Belz et al., 2017; Douglas et al., 2020), underscoring the ambition to explore, inhabit and become a multi-planetary species. While Wu et al. (2012) highlights future advancements in the 21st century, focusing on the engineering of bases on planetary bodies, Chen et al. (2021) argue that this represents only one aspect of humanity's aspirations. They suggest that establishing a sustainable, long-term human presence in space will also necessitate the construction of space habitats. Chen et al. (2021) review several space habitat designs, including torus, bola, and rotating cylindrical structures, emphasising that long-duration space missions bring considerable challenges, and that these must directly inform the required aspects of habitat design. Among these challenges, one of the most critical is the adverse physical and physiological effects of prolonged exposure to microgravity on the human body.

Chen et al. (2020; 2021) highlight challenges such as space motion sickness, stress, heightened stress levels, kidney stones, and cardiovascular deconditioning, while Angeloni and Demontis (2020) emphasise the need to understand endocrine adaptations to physical and psychological stressors to develop countermeasures for deep-space missions. The impacts of microgravity explored here ranges from immune dysregulation and bone loss. These challenges, compounded by vision impairment, muscle atrophy, and loss of traction as noted by Queijo et al. (1987; 1988) and furthered by Trappe et al. (2009), pose significant obstacles to the health of astronauts and crew, as well as the success of long-term missions. While exercise is currently employed on the ISS to mitigate some of these effects as a short-term countermeasure (Trappe et al., 2009; Chen et al., 2020), certain conditions remain unaddressed, such as vision impairment. Trappe et al. (2009) further highlight the limitations of existing exercise protocols and equipment, underscoring the need for improved strategies to better protect skeletal muscle health, while potentially reducing the time allocated to exercise, which currently consumes roughly 3.4% of the total orbit time.

Considering that the next half-century is expected to bring significant advancements in space exploration, the concept of a rotating space station emerges as a compelling solution. This progress may be comparable to the "competition period" described by Wu et al. (2012) and is particularly relevant as the ISS approaches retirement and decommissioning (Chen et al., 2021). The design proposed in this study utilises rotational motion to simulate Earth-like gravity, addressing the challenges posed by prolonged microgravity. Envisioning a future where such habitats can sustain crews for extended periods while enabling research, it becomes critical to explore advancements in procreation, and child development (Chen et al., 2020; 2021). While these domains require further research, the adoption of an Earth-like 1g environment in this study simplifies the process by closely replicating terrestrial conditions, making it easier to support a broader scope of human habitation in space.

1.2 Project Aims & Work Streams

This design study explores the feasibility, design principles, and operational strategies needed to develop a sustainable and habitable rotating space station that replicates Earth-like gravity. A study of this scale requires the integration of various critical subsystems. Queijo et al. (1987) identifies key components such as electrical power systems, Guidance, Navigation, and Control (GNC), structural and mechanical systems, thermal control, and communications and tracking subsystems. However, given the limited number of team members, certain subsystems are prioritised in this study. The selected subsystems and their contributions are summarised in **Table 1**.

Table 1: Initial Subsystem Allocations and Relevance to Design Study

Subsystem	Description
Attitude and Orbital Determination	Determining the orientation and orbit of the rotating space station, ensuring stability
Structural Design	Engineering of the space station's structural framework, including dimensions, and materials
Power Systems	Energy generation, storage, and distribution to ensure continuous power for all station operations
Thermal, Radiation & Shielding	Development of shielding systems to protect the crew and station from radiation
Life Support	Designing critical systems (e.g., food management)to sustain crew health and safety during long-term missions

The seamless integration of these prioritised subsystems is essential to achieving the project's overarching goal: establishing a foundational, preliminary design for a sustainable and habitable environment to support long-term space missions. It aims to address the challenges posed by prolonged exposure to microgravity, the project aims to advance space exploration and enable long-term human habitation in space.

2. Life Support Subsystem (LSS)

2.1 Importance of Subsystem

In crewed missions, ensuring the health and safety of the crew is of utmost importance. The intricate demands and narrow range of conditions required to sustain human life necessitate the development of a reliable and robust life support subsystem (Shuey and Standard, 1982; Mitchell, 1994; Chen et al., 2021). Shuey and Standard's (1982) study provides an overview of life support systems for long-duration space missions, identifying over 50 distinct functions essential for a space station. Here, this subsystem is described as one of the most critical, complex, and thermally demanding components, a perspective echoed by Mitchell (1994) and Chen et al. (2021). Functions such as environmental control, atmosphere revitalisation, water and waste management, food provisions, thermal regulation, and other essential safety and operational functions are encompassed within this subsystem, as highlighted in these studies.

The significance of the life support subsystem is further underscored by the proposed crew capacity for the space station, as the size of this subsystem is directly dependent on the number of crew members it must support (Shuey and Standard, 1982). Earlier studies by Queijo et al. (1987; 1988) introduced large, complex structures capable of advanced operations but limited to housing only 60 crew members. Given the scale and complexity of those designs, such a capacity appears underutilised. In contrast, the current design aims to significantly expand capacity, accommodating up to 192 members. This is achieved by housing six crew members per capsule within two oppositely rotating rings, each comprising 16 capsules. By nearly tripling the crew size, this design optimises the station's operational potential and efficiency. Consequently, the LSS becomes a critical focus of this study, addressing the challenges associated with supporting a substantially larger crew.

2.2 Bioregenerative Life Support Systems (BLSS)

As we move forward, it is essential for life support systems to evolve into self-sustaining, bioregenerative systems (Shuey and Standard, 1982; Mitchell, 1994; Chen et al., 2021). Hoff et al. (1982), Mitchell (1994) and Douglas et al., 2020 emphasise that developing a fully autonomous system, capable of eliminating reliance on resupply, is critical for the success of future space habitats—especially in situations where resupply from Earth is impractical or undesirable. While this level of autonomy may not yet be required for the proposed rotating space station—designed to closely replicate and extend the functions of the ISS within Earth's vicinity—it remains a critical goal for future habitat bases in free deep space, where Earth-dependent resupply would no longer be feasible (Belz et al., 2017). In a BLSS, Mitchell (1994) emphasises the advantages of centring the system on a plant-based vegetarian diet. Such an approach not only provides nutritional sustenance but also facilitates atmospheric revitalisation by generating oxygen and absorbing carbon dioxide. Careful selection of food crops is therefore crucial, focusing on species with high edible biomass yield, low waste production, and nutritional value, such as cereals, legumes, and vegetables such as potatoes and lettuce (Mitchell, 1994; Belz et al., 2017).

Shuey and Standard (1982) emphasise the importance of recycling and regeneration within life support systems, a requirement that becomes particularly critical in the context of a BLSS. As a closed-loop system, a BLSS must efficiently recycle organic waste into usable resources with minimal material loss (Mitchell, 1994). For example, plants release purified water vapour during photosynthesis, which can be captured, condensed, and reused. Furthermore, non-edible biomass from crops can be composted, though Mitchell (1994) underscores the importance of selecting crop species with minimal non-edible mass to optimise efficiency. This self-sustaining approach is essential for enabling long-term space habitation, reducing logistical dependencies, and ensuring a stable and renewable resource flow.

A conceptual system diagram of a BLSS, initially proposed by Hoff et al. (1982) and later refined by Mitchell (1994), is illustrated in **Figure 1**.

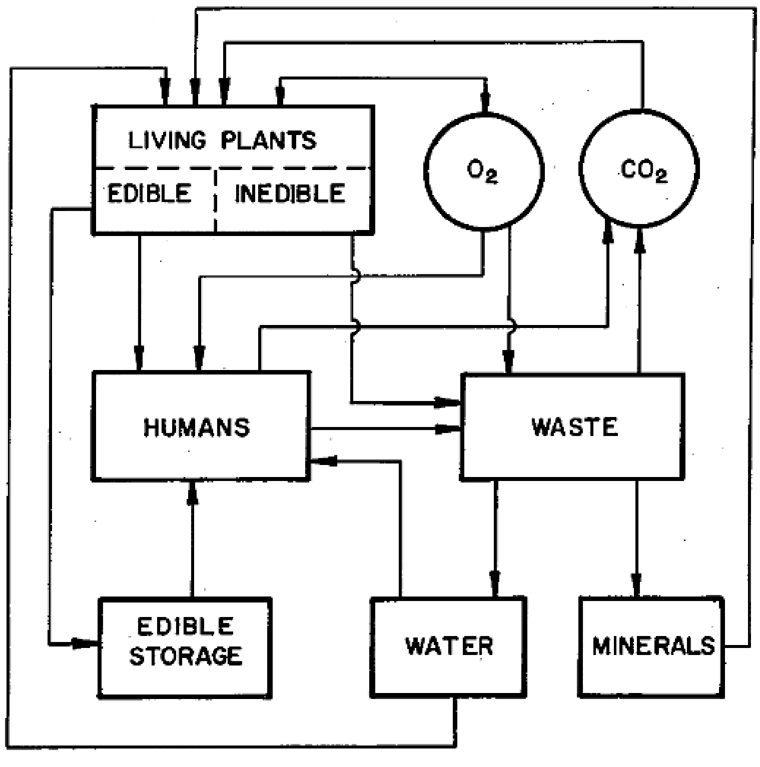

Figure 1: A Regenerative Life Support System Incorporating Higher Plants for Food Production and Air Revitalisation, as Proposed by **Hoff et al. (1982)**

To emphasise the management of organic waste, this diagram has been further adapted and is presented in **Figure 2**.

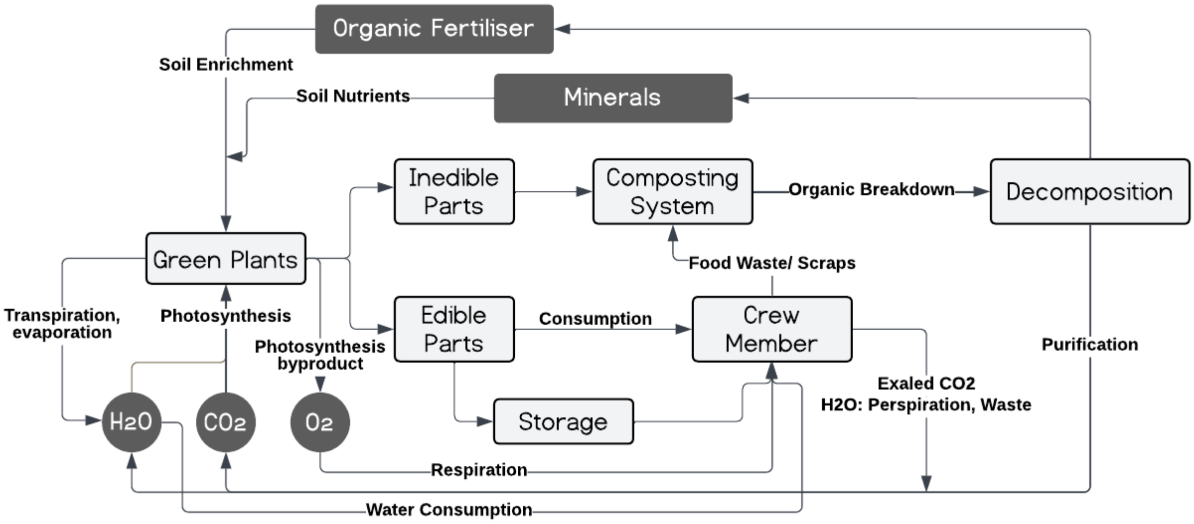

Figure 2: Enhanced Bioregenerative Life Support System Diagram Emphasising Waste Management Processes, (Adapted from **Mitchell (1994)**)

Two essential components are critical for the successful development of a closed-loop BLSS: crop growth and a composting system. This feasibility study evaluates the potential for integrating a bioregenerative, sustainable LSS within the rotating space station. For the purposes of this analysis, it is assumed that water management and air purification technologies are sufficiently advanced for integration into the rotating space station and are already in place. The following sections discusses the specific challenges and considerations related to these components, beginning with the composting system, with future avenues discussed after preliminary conclusions.

2.2.1 Composting System

Composting is a microbiological process that takes place under aerobic conditions, converting organic waste into stabilised compost through decomposition (Hogan and Finstein, 1991; Azim et al., 2018). This process involves the breakdown of materials such as human waste, food residues, inedible plant parts, and other biodegradable waste by microorganisms. In the context of this study, composting is specifically applied to inedible plant parts and food scraps generated during crew consumption. The process produces carbon dioxide (CO_2), water (H_2O), mineral nutrients, and heat, while significantly reducing the volume and weight of the original waste. The resulting stabilised compost can then be used to support plant growth, enrich soil fertility, tilth and structure (Hogan and Finstein, 1991). It is a cornerstone of a closed-loop life support system.

Hogan and Finstein's (1991) work hold particular relevance for the development of composting systems in space habitats. Their study focuses on designing a composting system suitable for space habitats, addressing the controlled decomposition of organic waste as part of a Controlled Ecological Life Support System (CELSS). The authors assume Earth-like gravity for composting processes, aligning seamlessly with the conditions expected in a rotating space station, thereby eliminating the need for significant refinements during integration. Additionally, their research presents a preliminary design addressing key factors such as ventilation, heat management, and batch processing, which provide a solid foundation for implementation. Hogan and Finstein (1991) advocate for "high, near-maximal" decomposition rates to minimise the risks of plant pathogens and odour generation while enabling a compact treatment facility—critical given the capsule dimensions of 44 m × 27 m × 16 m. Furthermore, the study highlights the integration of composting with other components of the life support system such as water purification and crop cultivation, demonstrating the potential for near-complete resource recovery in a closed-loop ecosystem.

Preliminary Design of Composting System

Figure 3 illustrates the preliminary design proposed by Hogan and Finstein (1991). The process begins with organic waste, such as inedible plant parts and food scraps, being introduced into a sealed composting chamber. Within this chamber, the composting matrix (comprising organic matter, air, and microbes) supports microbial activity as the microbes feed on the organic material. Forced airflow maintains aerobic conditions, with oxygen levels continuously monitored via an O_2 probe and adjusted to optimise efficiency. The system also acts as thermal insulation, capturing heat released during microbial activity. This heat elevation drives the transition from mesophilic bacteria to thermophilic bacterial activity, further accelerating the decomposition process.

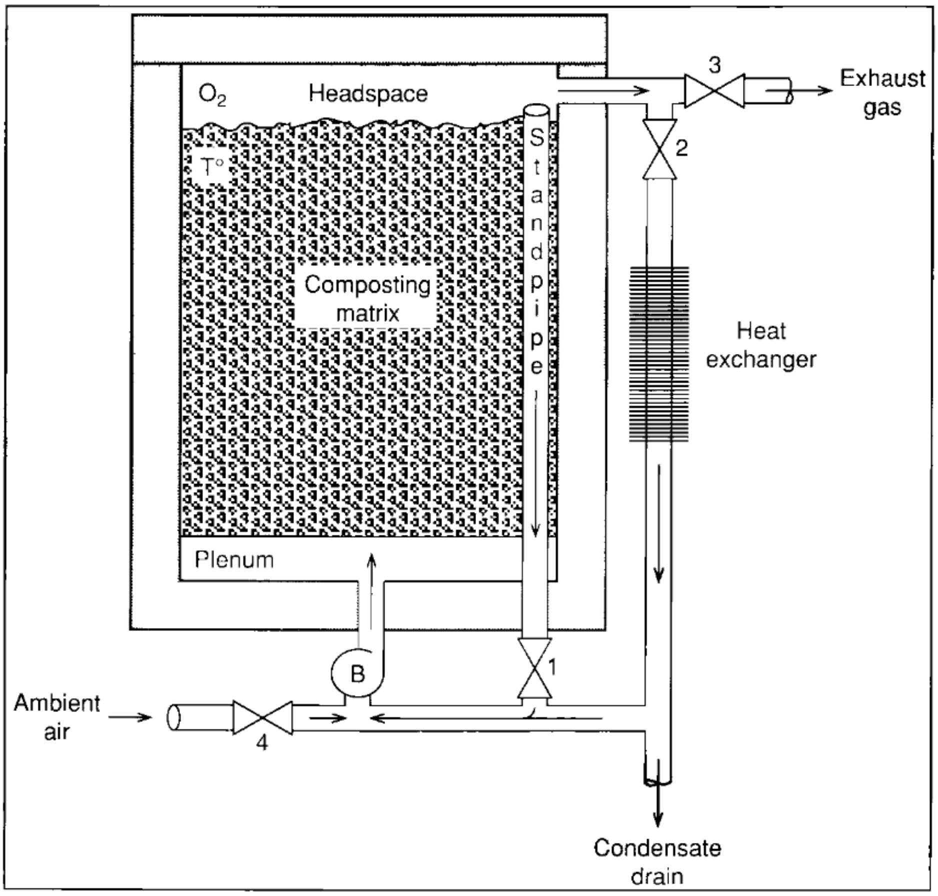

Figure 3: A conceptual design for a composting system tailored for space vehicles and habitats, as outlined by **Hogan and Finstein (1991)**

A network of control valves recirculates process gas through the compost matrix, promoting uniform oxygen distribution and minimising localised anaerobic zones that could lead to odour generation or pathogen growth. A summary of these control regimens is presented in **Table 2**. The following section discusses the operational specifics of this design, detailing how these regimens contribute to achieving high-efficiency decomposition.

Table 2: Summary of Conditions for Actuating Regimens and Corresponding Positions of Control Valves 1–4 Indicated on **Figure 3** (Table Reproduced from **Hogan and Finstein, 1991**)

Control Regimen	**Process Gas Condition**		**Control Valve Position**			
	O_2 (% v/v)	Temperature (°C)	1	2	3	4
#1	> 15	< 56	Open	Closed	Closed	Closed
#2	< 15	< 56	Closed	Closed	Open	Open
#3	> 15	> 56	Closed	Open	Closed	Closed

Control Regimens of the Composting System

In the initial stage (Process Control Regimen #1), both temperature and oxygen are maintained within ambient conditions, satisfying the thresholds set in **Table 2** (oxygen levels above 15% and temperatures below 56°C). During this phase, only valve 1 remains open, as outlined in **Table 2**, enabling the effective recirculation of process gas through the internal standpipe and blower (marked 'B' in **Figure 3**). This controlled airflow ensures uniform oxygen distribution, supports steady aerobic decomposition, and maintains temperature uniformity throughout the vertical profile of the chamber. As temperatures rise and microbial activity intensifies, aerobic respiration depletes oxygen levels, causing them to drop below 15% and actuating Process Control Regimen #2. In this phase, fresh ambient air is introduced into the chamber through the opening of valve 4, replenishing oxygen levels while displacing process gases, such as carbon dioxide, via the headspace through valve 3. The introduction of ambient air at approximately 20°C, combined with the removal of process gases, creates a vertical temperature gradient driven by enthalpy changes.

When oxygen levels remain above the threshold, but the temperature exceeds 56°C, the system transitions to Process Control Regimen #3. In this phase, process gases are routed through an external heat exchanger by opening valve 2. The heat exchanger cools the gases before recirculating them back into the chamber, effectively regulating the temperature without introducing new ambient air. During the cooling process, water vapour condenses, which is collected and purified within the water management/ purification system assumed to be on-board. As the composting process progresses, microbial activity diminishes due to substrate depletion. The system then alternates between Regimens #1 and #2 during this stabilisation phase, maintaining adequate oxygen levels and temperature control until the compost reaches full maturity. By this stage, the material is odour-free, biologically stable, and pathogen-free, making it suitable for use in soil to support crop growth. The chamber is then emptied, and the stabilised compost is removed, completing the cycle.

2.2.2 Crop Growth

From various habitat design concepts, agricultural space allocations per crew member have varied significantly. Biosphere 2 allocated 250 m² per person, while Space Village One proposed 300 m² (Chen et al., 2020; Soilleux and Gunn, 2017). More conservative values, such as 50 m² in Kalpana One and 61 m² in the Stanford Torus habitat, have also been explored. However, Chen et al. (2021) advocate for a range of 250 to 300 m² per crew member, arguing that it ensures diversity for cultural preferences and provides robustness against crop failure in a fully autonomous and sustainable life support system. Accordingly, this analysis adopts the 250 to 300 m² range as the basis for further considerations.

Agricultural Space Requirements

Each capsule is preliminarily designed to have three floors. Assuming maximum utilisation of floor space across all three floors, with 16 capsules per ring and two rings, the total available floor space is estimated to be 68,000 m². Additional capsule specifications are summarised in **Table 3**.

Table 3: Summary of Capsule Specifications

Number of Pressurised Capsules	32
Capacity per Capsule	6
Maximum Crew Capacity	192
Floors per Capsule	3
Dimensions of Capsule	44 m × 27 m × 16 m
Total Available Floor Space	≈ 68000 m^2 (44 × 16 per floor × 3 floors × 32 capsules)

Table 4: Summary of Agricultural Space Requirements

Category	Space Per Person (m^2)	Total Space Requirement (m^2)	Percentage of Total Floor Space
Conservative	250	48,000 (250 × 192)	71 %
Robust	300	57,600	85 %

Agricultural Energy Requirements

For the two crop space scenarios being considered and based on the agricultural light intensity values presented in **Table 5** (derived from Chen et al., 2020), the power requirements for agriculture are estimated at 30 kW and 36 kW per person for crop spaces of 250 m² and 300 m², respectively. For comparison, Biosphere 2, with 250 m² of crop space per person, estimates an agricultural power demand of 33 kW per person, while Kalpana One, with only 50 m² of crop space per person, requires 50 kW per person for agricultural power (Soilleux and Gunn, 2017).

Table 5: Summary of Agricultural Lighting and Energy Requirements per person

Agricultural light intensity	25,000 lux	
Solar energy intensity for crops	243 W/m^2	
Crop Space per Person (m^2)	250	300
Agricultural Power per Person	≈ 30 kW (250 × 243 × 0.5)	≈ 36 kW

Note, the calculations for personal agricultural power demand are derived as the product of the crop space per person and the solar energy intensity for crops (corresponding to 25,000 lux of light intensity). This value is then halved to account for the assumption that crops receive light for only half of a day-night cycle.

2.3 Preliminary Conclusions

In summary, **Section 2.2** evaluated the feasibility of a bioregenerative life support system (BLSS) from the perspective of closed-loop food provision. Two key components were identified: the composting system and crop growth. A preliminary review of the composting system was conducted, along with calculations for agricultural energy and space requirements. Hogan and Finstein's (1991) work provide a solid foundation for integrating a composting system into a rotating space station, serving as a proof of concept that a closed-loop BLSS may be feasible—provided crop growth systems are successfully developed and implemented. However, while the composting system appears to be a mature and viable component, a fully autonomous crop-based system currently faces significant challenges in delivering the variety and quantity of food required to sustain crew health and morale over extended missions.

Although the energy demand of 30–36 kW per person (see **Table 5**) appears manageable in comparison to the ISS's power capabilities, the agricultural space requirements of 250–300 m² per person, as proposed by Chen et al. (2021), pose significant challenges. For a station with a crew capacity of 192, this translates to 48,000–57,600 m², which constitutes 71–85% of the total available floor space (see **Table 4**). Such a commitment of resources could limit the station's operational flexibility and prioritisation of other mission-critical activities. Furthermore, challenges such as crop failures, pests, and environmental instability (Hoff et al., 1982) add additional risks that could risk food security for the crew. Until these crop cultivation systems (particularly those concerning higher plants) are further refined and rigorously tested over extended durations, complete reliance on bioregenerative agriculture for establishing a long-term sustainable system remains impractical, as noted by Chen et al. (2021).

Consequently, food resupply missions are recognised as a vital interim solution by Shuey and Standard (1982), Belz et al. (2017), and Chen et al. (2021). These missions address immediate dietary requirements and mitigate risks such as crop failures, acting as a safety net to ensure the crew's nutritional needs are met while crop growth technologies continue to mature. As advancements in crop cultivation systems are achieved, the role of resupply missions can evolve. Rather than solely delivering food, these missions could support other logistical needs, including the transport of research equipment, medical supplies, or station upgrades. This gradual transition reduces dependency on external supplies, paving the way for a more self-sustaining Life Support System (LSS) in the long term.

3. Insights into Future Work

Having established that resupply missions will be essential for food provision, it is evident that the life support system will rely on a hybrid approach—combining onboard crop cultivation with supplies transported from Earth. In this context, it is clear that the soil-based cultivation of higher plants on the rotating space station should advance beyond the experimental efforts currently seen on the ISS (Chen et al., 2021). Rather than merely testing growth conditions, future efforts should aim to achieve a significant level of production for crew consumption.

Determining the levels of resupply required, both in terms of frequency and payload capacity, will be a core focus for future research. In parallel, focus will expand to mission planning and the operational phases of these rendezvous missions, spanning launch, phasing, rendezvous, and docking (Fehse, 2003). Building on Fehse's (2003) foundational research on Rendezvous and Docking (RVD) Technology, this work will emphasise the development of advanced guidance, navigation, and control (GNC) algorithms. These will be complemented by the simulation and visualisation of trajectories using tools such as MATLAB/Simulink and Python, enabling precise approach and docking manoeuvres critical for mission success and operational efficiency.

4. Academic Integrity Certification

Figure 4: Academic Integrity (at Queen Mary 2024/25) Certificate of Completion

5. References

Angeloni, D., Demontis, G.C., 2020. Endocrine adaptations across physical and psychological stressors in long-term space flights. Current Opinion in Endocrine and Metabolic Research 11, 21–26. https://doi.org/10.1016/j.coemr.2019.12.005

Azim, K., Soudi, B., Boukhari, S., Perissol, C., Roussos, S., Thami Alami, I., 2018. Composting parameters and compost quality: a literature review. Org. Agr. 8, 141–158. https://doi.org/10.1007/s13165-017-0180-z

Belz, S., Keppler, J., Helisch, H., Bretschneider, J., Detrell, G., 2017. Innovative biological and physico-chemical recycling of CO2 in human spaceflight. Presented at the (47th) International Conference on Environmental Systems, Charleston, South Carolina.

Chen, M., Goyal, R., Majji, M., Skelton, R.E., 2020. Design and analysis of a growable artificial gravity space habitat. Aerospace Science and Technology 106, 106147. https://doi.org/10.1016/j.ast.2020.106147

Chen, M., Goyal, R., Majji, M., Skelton, R.E., 2021. Review of space habitat designs for long term space explorations. Progress in Aerospace Sciences 122, 100692. https://doi.org/10.1016/j.paerosci.2020.100692

Douglas, G.L., Zwart, S.R., Smith, S.M., 2020. Space Food for Thought: Challenges and Considerations for Food and Nutrition on Exploration Missions. The Journal of Nutrition 150, 2242–2244. https://doi.org/10.1093/jn/nxaa188

Fehse, W., 2003. Automated Rendezvous and Docking of Spacecraft, Cambridge Aerospace Series. Cambridge University Press.

Hoff, J.E., Howe, J.M., Mitchell, C.A., 1982. Nutritional and cultural aspects of plant species selection for a controlled ecological life support system. NASA Contractor Rep, 166324. https://api.semanticscholar.org/CorpusID:83064183

Hogan, J.A., Finstein, M.S., 1991. Composting of Solid Waste During Extended Human Travel and Habitation in Space. Waste Manag Res 9, 453–463. https://doi.org/10.1177/0734242X9100900164

Mitchell, C., 1994. Bioregenerative life-support systems. The American Journal of Clinical Nutrition 60, 820S-824S. https://doi.org/10.1093/ajcn/60.5.820S

Queijo, M., Butterfield, A., Cuddihy, W., King, C., Garn, P., 1987. An advanced technology space station for the year 2025, study and concepts. NASA Technical Reports Server, Langley Research Center.

Queijo, M., Butterfield, A., Cuddihy, W., King, C., Stone, R., Garn, P., 1988. Analysis of a rotating advanced-technology space station for the year 2025. NASA Technical Reports Server, Langley Research Center.

Shuey, M.A., Standard, H., 1982. Life Support System Considerations for Space Station, in: The Space Congress® Proceedings. Presented at the 1982 (19th) Making Space Work For Mankind.

Soilleux, R.J., Gunn, S.D., 2017. Environmental control and life support (ECLSS) for large orbital habitats: ventilation for heat and water and management, NSS Space Settlement Journal.

Trappe, S., Costill, D., Gallagher, P., Creer, A., Peters, J.R., Evans, H., Riley, D.A., Fitts, R.H., 2009. Exercise in space: human skeletal muscle after 6 months aboard the International Space Station. Journal of Applied Physiology 106, 1159–1168. https://doi.org/10.1152/japplphysiol.91578.2008

Wu, W., Liu, W., Qiao, D., Jie, D., 2012. Investigation on the development of deep space exploration. Sci. China Technol. Sci. 55, 1086–1091. https://doi.org/10.1007/s11431-012-4759-z