Canadian Food Production Subsystem Designs for a Lunar Agriculture Module - Ground Test Demonstrator (LAM-GTD)

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The ability to produce fresh food in situ will be a beneficial addition to the future of sustainable lunar surface exploration, reducing reliance on traditional physiochemical life support systems and pre-packaged food supplies from Earth. To advance Controlled Environment Agriculture technologies and crew operations in preparation for a Lunar Agriculture Module, the Canadian Space Agency and the German Aerospace Center have conceptualized and progressed the design of a Lunar Agriculture Module - Ground Test Demonstrator. The purpose of this high-fidelity demonstrator would be to increase the technology readiness levels of all major greenhouse subsystems, simulate crew operations, and inform engineering requirements for an eventual lunar surface design. Canada is planning to contribute to the design of several key subsystems, including the Nutrient Delivery System, the Light Control System, the Versatile Assistant robotic arm, a Plant Health Monitoring System, and technologies that could improve confidence in the module's food safety processes. This paper outlines the progress made to date on these key subsystems and how our teams intend to use the Lunar Agriculture Module - Ground Test Demonstrator to prepare for the challenge of a Lunar Agricultural Module.

Acronyms and Nomenclature

AMS	=	Air Management System
BLSS	=	Bio-regenerative Life Support System
CAD	=	Computer-aided Design
CEA	=	Controlled Environment Agriculture
CES	=	Concurrent Engineering Study
COTS	=	Commercial off-the-shelf
CSA	=	Canadian Space Agency
DHCS	=	Data Handling and Control System
DLR	=	German Aerospace Center
EC	=	Electrical Conductivity
EDEN	=	Evolution and Design of Environmentally closed Nutrition-sources
ePAR	=	Extended Photosynthetically Active Radiation
EPS	=	Electric Power System
LAM-GTD	=	Lunar Agriculture Module - Ground Test Demonstrator
HabSim	=	Habitat Simulator

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HVAC	=	Heating, ventilation, and air conditioning
ISS	=	International Space Station
LAM	=	Lunar Agriculture Module
LCS	=	Lighting Control System
LED	=	Light Emitting Diode
MCC	=	Mission Control Center
NASA	=	National Aeronautics and Space Administration
NDS	=	Nutrient Delivery System
NDVI	=	Normalized Difference Vegetation Index
NFT	=	Nutrient Film Technique
NRC	=	National Research Council
PAR	=	Photosynthetically Active Radiation
PPFD	=	Photosynthetic Photon Flux Density
RH	=	Relative Humidity
TCS	=	Thermal Control System
VA	=	Versatile Assistant

I. Introduction

The Canadian Space Agency's (CSA) Food Production Initiative (FPI) and the German Aerospace Center's (DLR) Planetary Infrastructures Group have been steadily progressing planning efforts towards the design of a Lunar Agriculture Module - Ground Test Demonstrator (LAM-GTD). The purpose of the LAM-GTD will be to increase the Technology Readiness Level (TRL) of all key greenhouse technologies required to generate a wide variety of fresh crops for crew consumption and simulate lunar operations in a one-of-a-kind fully integrated testing platform. The LAM-GTD will build upon lessons learned from other terrestrial demonstrators including EDEN ISS MTF[1,2], the Biomass Production Chamber[3], and the MELiSSA program[4]. Rigorous operations campaigns planned for the LAM-GTD will provide engineers and scientists with an opportunity to further refine the system design and concept of operations before applying these lessons towards a space-qualified Lunar Agriculture Module (LAM). Thus, the LAM-GTD would not serve as an engineering model for the LAM but as a necessary and iterative demonstrator towards ground truthing reliable bioregenerative life support systems (BLSS) for the Moon and eventually Mars. Currently, the LAM-GTD infrastructure is planned to consist of four key components, each providing a core functionality to be demonstrated (Figure 1). The first component, a Ground Agriculture Module (GAM), would contain all the technologies required to support high-density crop growth. The second component, an Airlock Module (ALM), would allow operators to modulate atmospheric pressure and gas composition to ensure consistency with planned exploration pressures (57-70 kPa) for lunar surface infrastructure[5]. The third component, a Habitat Simulator (HabSim), would allow the study of resource exchanges (e.g., oxygen, carbon dioxide, water) between the agricultural module and a simulated human habitat. Finally, the fourth component, a Mission Control Centre (MCC), would allow tele-operation of the LAM-GTD infrastructure from Canada, Germany, and other participating agencies. The LAM-GTD infrastructure will be designed with mobility in mind, to be initially installed in one of the participating agency countries, with the possibility of moving to another site(s) in the future. The conceptual design studies for the LAM-GTD have been conducted bilaterally between CSA and DLR, with informal participation from space agency subject matter experts such as NASA and ASI. At this stage, our international team is open to additional formal collaboration. While the GAM, ALM, HabSim and MCC are required to operate the LAM-GTD, the focus to date has been on the design of the GAM, and this paper will outline our design progress.

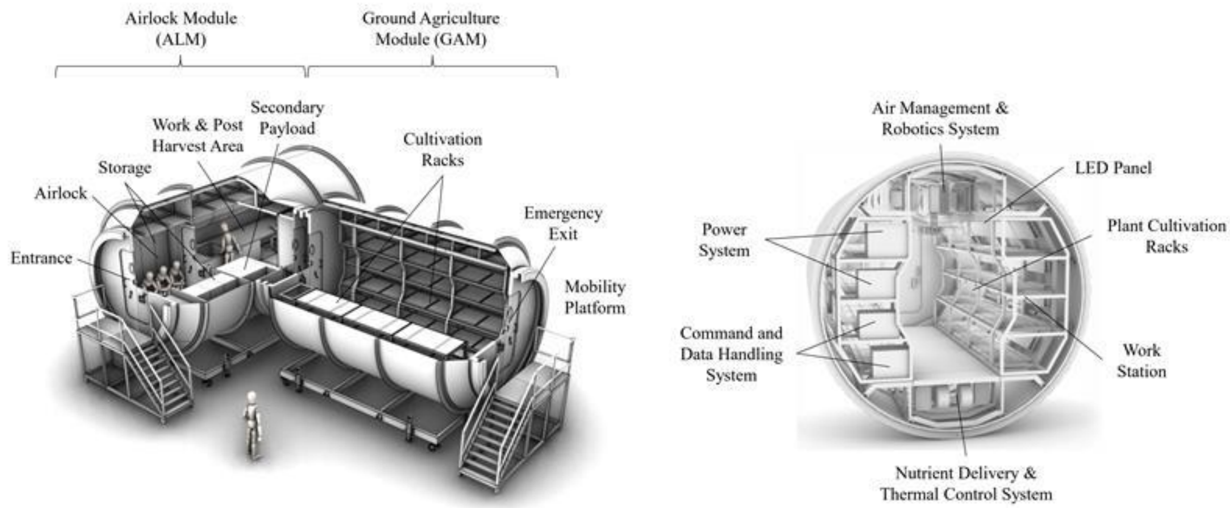

Figure 1. Left) Lunar Agriculture Module Ground Test Demonstrator infrastructure render. Right) A cutaway view of the Ground Agriculture Module highlighting various planned subsystems.

II. Canadian Contributions to the Ground Agriculture Module

The GAM component of LAM-GTD must autonomously create, manage and maintain an optimal environment for high-density, high-quality crop growth. This functionality will require many environmental control hardware subsystems, robust climate control software, and research-based horticultural management strategies. Having established the purpose, objectives and initial requirements for the GAM, the next step was to divide the design work packages between the Canadian and German agencies. At this stage, the CSA FPI has agreed that Canada would be responsible for the design of the Nutrient Delivery System (NDS), the Light Control System (LCS), the Plant Health Monitoring (PHM) System, and the Versatile Assistant (VA) robotic arm. While DLR's Planetary Infrastructure Group will focus on the design of the structure, Air Management System (AMS), Thermal Control System (TCS), Data Handling and Control System (DHCS), and Electric Power System (EPS). The CSA FPI has been able to advance the design work for the GAM through competitive contracts, with all Canadian industry, academia, and space sector able to apply. The CSA FPI awarded the initial design contract for these subsystems and has been managing this effort since 2023. The following sections will summarize some of the current design thinking towards the NDS, LCS, PHM, and VA subsystems, including assumptions, requirements, and trade-off analyses performed.

A. Nutrient Delivery System

Crop production requires a reliable and near constant supply of nutrient solution for healthy growth and development. The hardware and software subsystem responsible for monitoring, maintaining, delivering and recirculating nutrient solution is referred to as the NDS. The NDS for GAM will directly build upon the design elements and lessons learned from DLR's EDEN ISS greenhouse deployed and operated in Antarctica from 2018-2022[1,2]. The NDS design will focus on improving system reliability, simplifying operation, and reducing crew maintenance requirements. Conventional NDS components include the plant growth trays, the piping, the bulk solution tanks (i.e., fresh, waste, solution, additives), the mixing computer, the pumps, and the sensors. While our teams are still in the planning stages, significant progress has been made towards determining a potential layout and selection for these components (Figure 2).

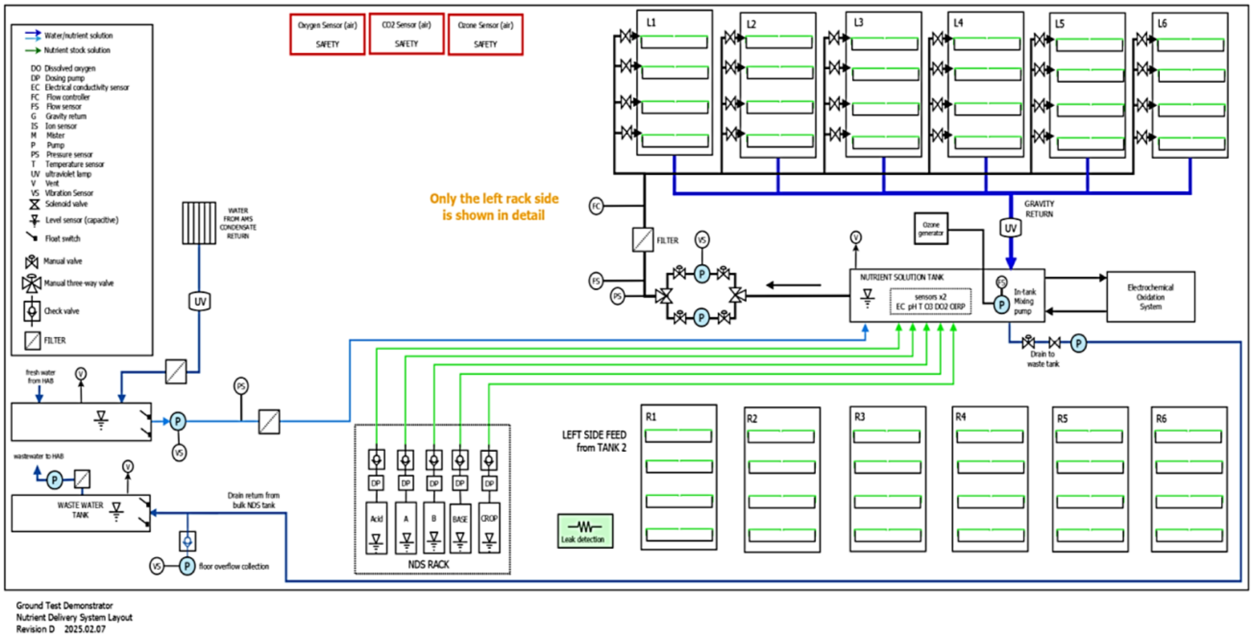

Figure 2. Nutrient Delivery System piping and instrumentation design for the Ground Agriculture Module.

The GAM's NDS system will be designed to support up to 25 m^2 of high-density, high-quality crop production. The crop growth area will be evenly distributed amongst 48 trays (700 mm x 700 mm x ~80-100 mm) with 24 trays on each side of the GAM (6 columns x 4 levels). While smaller trays are preferred for crew handling, a larger size was selected to reduce the number of connections and piping required. Columns of trays will share common input and output lines to reduce overall piping complexity (Figure 2). Input lines to the growth trays are planned to be routed through the support frame. Solenoid valves are planned to be installed below the racks to allow for targeted irrigation events and ease of maintenance. All tray interfaces will be in the front of the tray for ease of operation, maintenance, and automation. Currently, a single standardised tray design that will be acceptable for the wide variety of crops to reduce system complexity was chosen. Each tray will have three subcomponents, a lid with regularly spaced holes to support the plant holders for both larger and smaller crops, a root zone tray with several water channels that will contain the nutrient solution and plant roots, and a drip tray that rests below the root zone tray to collect nutrient solution and guide it back towards the drain line. A potential failure mode to consider in any plant production system is flooding caused by root clogging of drainage ports. This risk is mitigated by the use of large drain holes and a drain tray system that drains opposite the growing tray's drains, thus creating a long path for roots to grow before reaching the main drain. Proper time management and effective harvesting practices will further minimize the risk of flooding from the trays. Individual trays are designed to slide out to facilitate plant maintenance, harvesting, and cleaning of the system, as well as eliminate the need to move trays to a separate work area for standard tasks. Additional trade-off analyses performed when making NDS design decisions are presented below (Table 1).

Table 1. Nutrient Delivery System design trade-offs considered.

Option(s) Considered	Option Selected	Option Rejected
Aeroponics vs. Nutrient Film Technique	Nutrient Film Technique: Low pressure pumps are generally more reliable, cheaper, and easier to replace.	Aeroponics: High-pressure pumps are more expensive and prone to failure with repeated cycling. Reduced capacity in case of pump failure.
Tray piping connections location Front vs. Back	Front: Ease of maintenance, visual inspection, and operations.	Back: While pipes would be out of the way, any adjustments would require operators to reach to the back of the system or disassemble racking.

All other major components of the NDS including the tanks, mixing computer, sensors, and pumps are designed to be located in the sub-floor of the GAM to maximize the available area for crop production. This configuration also facilitates the gravity return of the nutrient solution, eliminating the need for an additional return pump. Three large tanks are planned for the sub-floor: a bulk nutrient solution tank, a wastewater tank, and a freshwater tank. In addition, several smaller tanks will hold concentrated acid, base, and nutrient stock solution required to maintain the bulk solution quality. Nutrient solution transport throughout the system will be controlled by the mixing computer, which integrates data from various sensors located within the larger tanks. These sensors are planned to monitor key parameters, including electrical conductivity (EC), pH, temperature, dissolved oxygen levels, and flow rates. For disinfection, UV-C light-emitting diode (LED) units will treat recirculated irrigation water from the growth area, as well as water in the nutrient tanks and condensate from the Air Management System (AMS). Additionally, the bulk solution tank will be equipped with an electrochemical oxidation unit that generate ozone in solution. Several pumps will be incorporated into the NDS system, including two pumps installed in parallel to deliver nutrient solution from the bulk solution tank to the plant trays, providing redundancy. A third pump is planned for draining the nutrient solution tank and a fourth is planned to supply the ozone generator. As a safety measure, dedicated ozone sensors will be implemented within the system indicating when it is safe for the crew to enter.

Preliminary mass and power estimates for the system are approximately 420 kg and 610 W, respectively. Some components of the NDS remain to be determined, with the largest unknown contributor to the power budget being the tank heaters. The sizing of these heaters will depend on the envelope insulation of the GAM and the external environment at the final installation location. The projected mass of the heating elements is expected to be negligible. A nutrient tank cooling is also being considered to maintain optimal dissolved oxygen levels for plant productivity,

B. Lighting Control System

The critical hardware and software subsystem required to provide and distribute light for high-density plant growth throughout the GAM is referred to as the LCS. Recent advances in LED technology for industrial Controlled Environment Agriculture (CEA) applications, such as vertical farms and greenhouses, have led to the development of compact, energy-efficient, variable-spectrum LED arrays suitable for the GAM. These advanced LED arrays facilitate programmable control of the light environment, including intensity, spectrum, and photoperiod, and can be positioned near the canopy without causing damage to plant tissue. Additionally, research has demonstrated that the light environment (intensity, spectral distribution, photoperiod, and canopy distribution) has a significant impact on plant growth rates, morphology, and yield[6-8]. The GAM will incorporate a dynamic LED-based LCS, and the current design efforts for this subsystem are outlined as follows.

Each of the 48 plant growth trays will be equipped with a dedicated LED array capable of providing a consistent and evenly distributed light environment, optimized for plant production. A compact, low-profile, water-cooled LED array is proposed to reduce mass, area, and volume, thus maximizing vertical growth area for plants. The LED array will be custom-built with dimensions of 500 mm x 650 mm x 30 mm (0.36 m³). Tempered water will flow through a distribution manifold on one side of the array, with a receiving manifold on the opposite side, to manage heat being produced (Figure 3). Proper sizing of both manifolds will ensure uniform flow through the LED tubing.

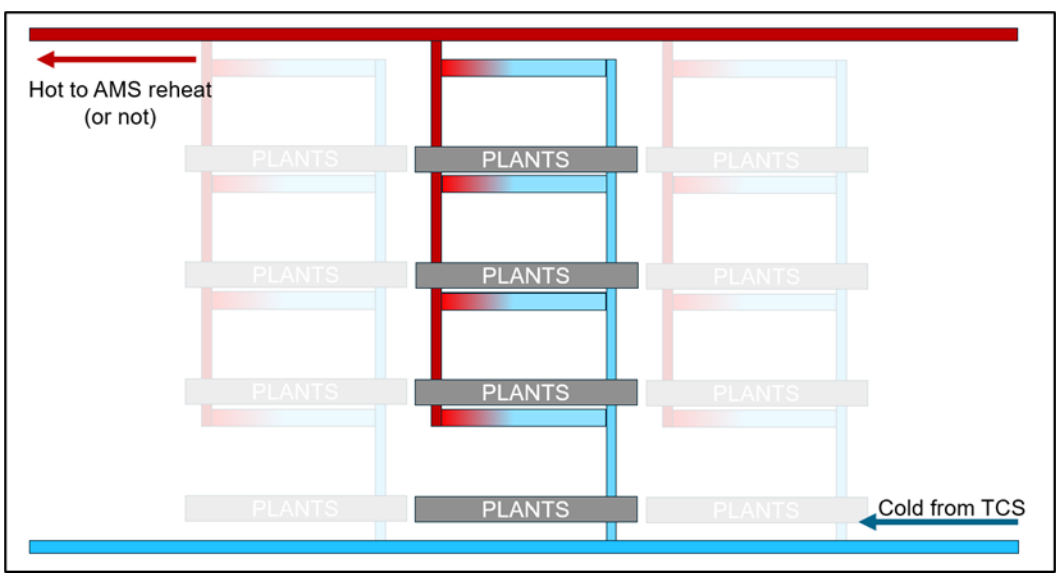

Figure 3. Water-cooling flow diagram for Light Control System of the Ground Agriculture Module.

To streamline power supply and distribution, the GAM will provide all subsystems with 28VDC power, as it is safe-to-touch and a quasi-standard in space satellite systems[9]. Utilizing a low-voltage DC power supply allows the LED arrays to be powered directly, thereby eliminating the need for bulky drivers or ballasts. This design decision significantly reduces both the mass and power requirements of the LCS, as drivers and ballasts are typically heavy and exhibit inefficiencies during the conversion from AC to DC power. The total system power required by the LCS is directly dependent on the light intensity required for the crops that will be cultivated within the GAM.

An innovation planned for the LCS is the integration of PHM sensors and fans directly into the LED array. Integrated sensors will provide real-time feedback from the plants, enabling ongoing assessment of their health and productivity, which will be discussed further in the PHM section. Sensors will also monitor array status and in the event of an array over-temperature condition, the LCS controller will independently trigger an emergency stop and notify the DHCS during data transmission. Data processing, storage, and LED control inputs will be managed by the DHCS. The DHCS will communicate wirelessly (protocol to be determined) with the LCS controller, enabling adjustments to spectrum, intensity and photoperiod. Data transmission will occur on request from the DHCS to the LCS, as needed.

Light spectrum and intensity are the most critical factors influencing plant development and productivity. A three-channel LED array has been selected to support optimal plant growth while offering spectral flexibility to customize conditions for vegetative and flowering processes. The first channel, a high blue-content white LED (e.g., cool white with a 5500K profile), provides a general spectrum conducive to most plants' growth and supports human and camera vision for crop inspection. The second channel, a red LED, targets a portion of the Photosynthetically Active Radiation (PAR) spectrum known to be highly efficient in terms of power and net photosynthesis, thus enhancing the white LED spectrum[6-8]. The third channel, in the far-red region, plays a role in leaf expansion, cell elongation, and flowering for certain plant species[10]. This combination of white, red, and far-red LEDs delivers a full spectrum across both PAR and extended PAR (ePAR) wavelengths. Regarding light intensity, most plant canopies reach saturation at a Photosynthetic Photon Flux Density (PPFD) range of 400–800 μmol m^2 s^{-1}, where further light addition does not increase photosynthetic rate[4]. Consequently, the LCS control system will allow for dimming within the 0–800 μmol m^2 s^{-1} range, tailored to the specific crop being cultivated. Additional trade-off analyses performed when making LCS design decisions are presented below (Table 2).

Table 2. Lighting Control System design trade-offs considered.

Option(s) Considered	Option Selected	Option Rejected
Number of LED channels: Three channels vs. many channels (e.g., green, blue, amber, UV)	Three channels: Less spectral flexibility but sufficient for plant growth and significantly reduces the cost per array.	Many channels: Each channel adds complexity, mass, and cost to the array design.
Type of cooling: Water vs. air cooling	Water-cooling: More efficient method of heat dissipation, low profile array designs, but additional connections required.	Air-cooling: Large heat sinks, fins, and fans required to dissipate heat within the module; additional fans would be required.

There are still several open questions regarding the LCS design. For example, waste heat from the LCS could be transferred to the AMS reducing the strain on dedicated heating units. While this will increase the efficiency of energy usage within the GAM, it will significantly increase system complexity. While wireless communications between the DHCS and LCS are being considered, having 48 individually controlled arrays will be more complex than wired control.

C. Plant Health Monitoring

While tending to plants has been demonstrated to be beneficial to mental health and overall well-being, it is counterproductive for astronauts to dedicate most of their time to greenhouse operations. For this reason, the proposed greenhouse module will implement an autonomous PHM system. The PHM system will consist of a suite of camera hardware (e.g., visible, multispectral, hyperspectral, and infrared) and robust image processing software to create actionable tasks from this data. The PHM will facilitate real-time assessment of plant performance, alert the on-site operator to critical tasks, and enable remote observation by ground crew. Additional requirements for the PHM are expanded upon below:

- Have the ability to continuously monitor crop growth and performance throughout the growing cycle,

- Capture, store, and process images to detect early signs of crop stress, predict days to harvest, fruit ripeness and/or signs of necessary preventive system maintenance,
- Have the ability to independently operate and control up to 100 visible spectrum cameras simultaneously,
- Ensure that the cameras have a minimum still resolution of 8 MP and a minimum sensor resolution of 3280 × 2464 pixels,
- Have the capability to independently operate and control multispectral camera(s),
- Have the capability to independently operate and control thermal camera(s),
- Have a minimum acquisition frequency of 2 times per day for all cameras and include sufficient data storage for one year, and
- Integrate with the LCS and VA system interchangeable tools for mobile PHM assessments.

A comprehensive review of commercial off-the-shelf (COTS) imaging systems was conducted to determine potential options given the PHM system requirements. Several visible light cameras were procured and tested for more detailed review and analysis, all of which were relatively low cost. Early testing of these cameras aimed to help understand the imaging requirements, such as useful spectral ranges, optimal fields of view, or spatial constraints. The use of these cameras in conjunction with each other, when compared, facilitates the identification of the most desirable features and those required to meet the imaging needs of the GAM prior to the purchase of more expensive equipment. While individual cameras may not match the performance of hyperspectral and/or multispectral cameras, their combined capabilities cover a wide range of light and offer different fields of view and image resolutions. This approach allowed a more practical, data-driven comparison of camera specifications using real image data. Camera coverage spans the visible and near-infrared, with some models extending into the thermal region to explore potential benefits and added redundancy in thermal monitoring.

Preliminary estimates suggest that approximately 100 cameras will be required to adequately cover the 48 plant growth trays within the GAM (Figure 4). During operation, the PHM is estimated to have a total power consumption of 410 W and a weight of 7 kg. However, the final camera sensor has yet to be determined and these numbers are subject to change. The PHM sensors selected will be incorporated into the LCS LED arrays to reduce the wiring complexity while giving them the ability to image plants directly below. The PHM and LCS will communicate to ensure that the lighting conditions are optimal for the type of PHM data to be collected. In addition to the visible spectrum cameras mounted within the LED arrays, near-infrared camera sensors are planned to monitor plant growth and canopy development below. Sonar and/or LIDAR based sensors can be used to monitor plant height.

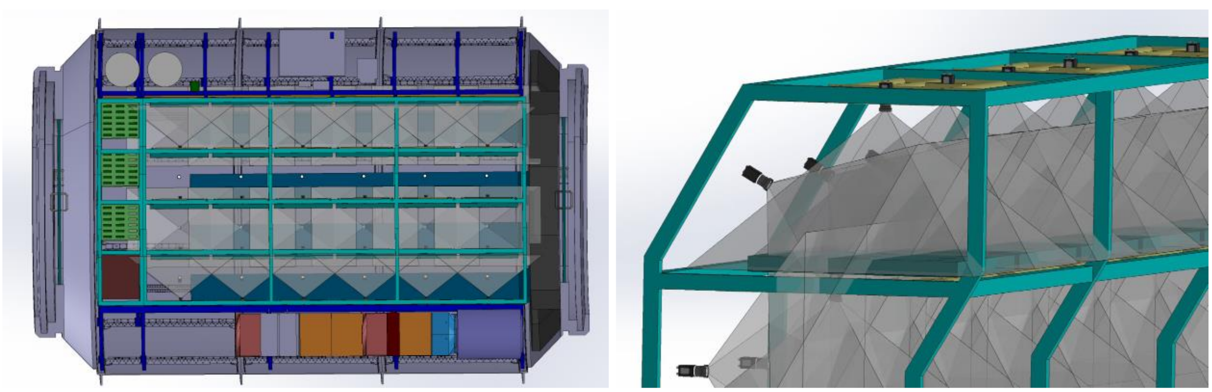

Figure 4. Plant Health Monitoring camera positioning and field of view coverage within the Ground Agricultural Module.

The present study will build upon the findings of the preceding review of academic literature by further investigating the capabilities of the purchased cameras to assess their usability in relation to different image data. The aim is to explore the potential of these cameras to extract data from more affordable and readily available options, thereby extending the limits of data extraction. Our review will continue with a particular focus on cameras and other spectral monitoring systems for precision agriculture and plant health, with the aim of refining and validating the selected cameras. The aim is to eventually have the capability to extract additional data from single camera systems, as well as to overlay images from multiple cameras, which may have a similar capacity to the more expensive and heavier commercial systems.

D. Versatile Assistant – Robotics

As astronauts will often be occupied with time-consuming tasks on the lunar surface, automation will be a key factor in the success of the mission. Therefore, all LAM-GTD infrastructure must be designed with autonomy in mind, considering that future greenhouse modules may be uninhabited or unoccupied for long periods between missions. The GAM will require a VA to operate autonomously and assist with crop production. This VA will consist of a mobile robotic arm to tend crops and remotely perform PHM activities with a scientific camera module, in addition to system related tasks. The ideal system should strike a balance between using current COTS technology and taking advantage of the knowledge and progress already made by DLR in the field of robotics (i.e., end effectors). When reviewing and evaluating possible COTS solutions, the following requirements were considered:

- Have a maximum mass of 60 kg,
- Have a power budget of 150 W (nominal); 250 W (peak),
- Be capable of both manual and autonomous operation, e.g., for planting, harvesting, decision making, navigation and preventive maintenance,
- Have a range of motion of at least 180˚ horizontally and 180˚ vertically, and
- Be compatible with specific hardware subsystems to be developed by DLR, such as interchangeable end effectors.

Currently, the proposed VA will be an un-braked COTS 6-axis collaborative robot (Co-bot) arm (Figure 5). The robotic arm can provide a highly reliable and capable solution and is a mature product already being used in the commercial market. To produce a bespoke robotic arm of similar size and reliability in-house would require considerable time, effort, and funding. The robotic arm would move along the length of the central corridor via a ceiling-mounted gantry, effectively 'suspending' the VA. This gantry would be propelled by an electrified rail powered by 28VDC from the EPS. The electrified rail proposed would be mounted to support struts spanning the distance from the ceiling to the primary structure. The speed of movement is expected to be in the order of 5-10 cm/s.

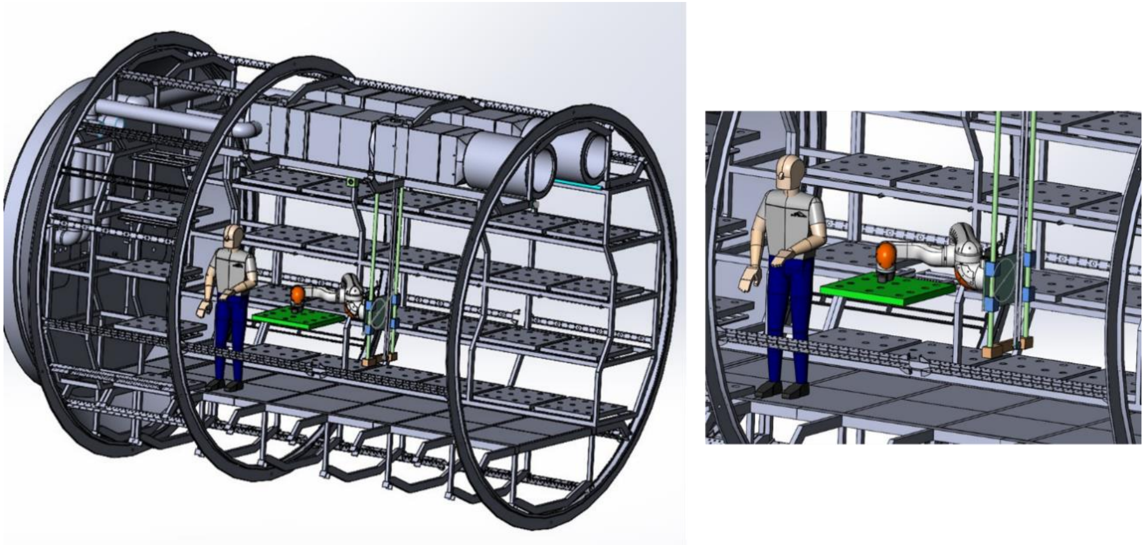

Figure 5. Versatile Assistant robotic arm potential configuration within the Ground Agriculture Module.

The VA would use an inverted telescopic lift to lower the entire robotic arm to the floor providing access to the lower levels of the plant growth racks (Figure 5). It is proposed that a combination of robotic arm and inverted telescopic lift is suitable as it allows for a smaller, potentially nimbler robotic arm, and reduces the lifetime travel distance of the robotic arm by eliminating much of the travel in the vertical plane by transferring this responsibility to the lift. It is proposed to divide the lift into three telescopic segments (each ~50 cm in length), which would extend to a final length of ~150 cm. The robotic arm itself is also expected to have a reach of ~150 cm, giving the VA a total reach of ~300 cm when fully extended. When not in use, the VA will reside in a designated "home base". This area is expected to occupy the conical area between the primary and secondary structure.

It is assumed that the VA will have access to three end effectors but will only be able to use one at a time. The two end effectors that are not in use are stored in a dock, which is also notionally located at the home base. Each end effector will have different characteristics that enable it to perform a specific set of operations, with one end effector assigned to each of the following operations:

- Plant maintenance/harvest,
- System maintenance, and
- Plant health monitoring.

The use of multiple end effectors increases redundancy against a single point of failure and allows flexibility in the plant and system tasks that can be performed. In addition, it is less likely that the payload capacity of the arm will be exceeded, as the tools required to perform the various operations can be spread across multiple end effectors, rather than being consolidated on a single massive end effector. It is not anticipated that the VA will be required to lift entire plant growth trays at any time. A minimum payload mass of 3 kg is currently assumed as a baseline.

The VA is intended to operate automatically, following a pre-defined path/imaging schedule, while simultaneously scanning for new obstacles (i.e., new plant growth) using LIDAR and visual imaging sensors. Manual tele-operations should be required to perform tasks such as general plant maintenance (transplanting tele-operations should be automated), GAM system maintenance and potentially some plant harvesting. Additional trade-off analyses for the VA design are presented below (Table 3, Table 4, and Table 5).

Table 3. Trade-off for the mode of mobility (key benefits are in bold).

Ceiling Mounted Gantry (Selected Option)	Wheeled Floor System	Inch-Worm
Existing heritage from EDEN Luna with a straightforward design philosophy; **Relatively fast implement/development time**	New system, but with a straightforward design philosophy; **Relatively fast implement/development time**	New system with several open design questions (number of segments, custom-made mounting points); Relatively long implement/development time
Rail guided, unlikely to get stuck	Potential to get stuck, significant localization issues	Potential to get stuck, significant localization issues
None, or very little, exposed cables (if included at the design phase)	None, or very little, exposed cables (if included at the design phase)	None, or very little, exposed cables (if included at the design phase)
No battery, direct power line	Battery and charging dock (battery fire risk)	No battery, but multiple power and data points with large harness
Highest overall mass (estimation)	**Lowest overall mass (estimation)**	Medium overall mass (estimation)

Table 4. Trade-off for methodology of data transfer (key benefits are in bold).

Wired (Ethernet) (Selected Option)	Wireless (Wi-Fi)
More reliable; **Redundant cabling reduces single point of failure.**	Single point of failure
Harness required (additional mass and cable management)	**No, or very minimal harness**
High speeds of data transmission	**High speeds of data transmission**
Less expensive hardware	More expensive hardware
Single hardware component to network connection required	No need for multiple hardware components to connect to a network for this subsystem
More secure (privacy)	Less secure (privacy)

Table 5. Trade-off for power source (key benefits are in bold).

Battery	Direct Power Draw (Selected Option)
Potential for battery fire	**Elimination of potential for battery fire**
Limited lifespan of battery	**Power source will not be the limiting factor for VA lifespan**
Less wiring	More wiring
Requires additional infrastructure for recharging	**Does not need additional recharging infrastructure**
Shorter duration operations due to the need for recharging	**Longer duration operations**
Battery imposes significant mass	Electrified rail (in place of battery) imposes significant mass

There remain several open issues in the conceptual design of the VA subsystem, which are expected to be addressed in future work. While some of the open issues are specific to the VA, others are not but may have an impact on the form/function of the VA. These open issues are:

- Waste handling (i.e., vacuum attachment may be required if assumptions change),
- Harvesting (i.e., harvesting via an automated, human, or hybrid approach),
- User interface,
- Calibration of sensors,
- Grasping strength, and
- Identify gaps in end effector design.

III. Next Steps for the LAM-GTD

The CSA's FPI plan is to focus on the continued refinement of the subsystem designs for the NDS, LCS, PHM system, and VA. Regular meetings and design reviews are planned to assess progress, ensure alignment with project objectives, and address any technical or operational challenges. These meetings would provide a structured forum to evaluate subsystem designs and ensure their optimization for integration into the larger LAM-GTD infrastructure.

There is significant potential for further collaboration with other space agencies, to bring additional expertise in critical areas such as agricultural system modelling, climate control and resource exchange studies. The involvement of these collaborators will enhance the design process, provide valuable insights, and accelerate the technology development for the LAM-GTD and its eventual transition to a space-qualified LAM.

In addition, ongoing assessments of the performance of the integrated system across the GAM, ALM, HabSim and MCC will be critical in validating the system's ability to simulate lunar operations. This iterative evaluation will ensure that any necessary adjustments are made prior to the final design phase. By focusing on system autonomy, sustainability and bioregenerative life support reliability, these steps will help prepare the LAM-GTD. Ultimately, it is expected that these efforts would contribute to the successful deployment and operation of human missions beyond Earth.

IV. Conclusion

The LAM-GTD represents a critical milestone towards advancing bioregenerative life support systems for lunar and Mars exploration. Through the collaborative efforts of the CSA and DLR, the work is making significant strides in the design of key subsystems necessary for sustainable food production in space. The GAM, along with the ALM, HabSim, and MCC, could form a comprehensive and integrated testing platform that would not only simulate lunar operations but also refine essential greenhouse technologies. The continued focus on the design of the GAM, particularly the NDS, LCS, PHM, and VA, reflects CSA's ambitions to developing autonomous systems that would support high-density crop growth for crew consumption. The insights gained from the ongoing design phases will provide invaluable data to inform the future development of a space-qualified LAM, ultimately contributing to enabling long-duration missions beyond Earth. The LAM-GTD infrastructure, once realized, could be instrumental in ensuring the reliability of food production systems for future lunar and Mars habitats, paving the way for sustainable human exploration of the Moon and Mars.

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