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MarsOASIS: A predeployable miniature Martian greenhouse for crop production research

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In order to enable long term habitation on planetary surfaces, a means of sustainable food production must be developed. The MarsOASIS greenhouse concept evolved to research crop production and serve as a proof of concept for larger scale food production facilities that would support manned missions to the surface of Mars. Utilizing in situ resources such as the Martian atmosphere, sunlight, and UV-C radiation, the greenhouse aims to provide a sustainable method of long-term food production requiring minimal consumable resources. The MarsOASIS system is capable of growing a full life cycle of Outredgeous lettuce with its autonomous control system designed for an unmanned environment and the option for teleoperation. A reduced-scope prototype of MarsOASIS is being developed to test technologies such as natural/artificial hybrid lighting, water recycling, remote teleoperation, and fully autonomous monitoring and control of the greenhouse. The prototype is currently in the final stages of design, with a full demonstration of plant life cycle testing set to occur in summer 2015. Results from this prototype demonstration will help quantify the feasibility of the innovative approaches incorporated in the MarsOASIS design.

Nomenclature

COTS = Commercial Off the Shelf
CU = University of Colorado at Boulder
DSN = Deep Space Network
HSST = Habitat Sensing Specifications Table
ISRU = In Situ Resource Utilization
ISS = International Space Station
GUI = Graphical User Interface
LED = Light-Emitting Diode
LGH = Lunar Greenhouse
MCLSS = Martian Crop Life Support System
OASIS = Optimized Agricultural System for In situ Specialization
PAR = Photosynthetically Active Radiation
PEEK = Polyetheretherketone
PSA = Pressure Swing Adsorption
STP = Standard Temperature and Pressure
UV = Ultraviolet
X-Hab = Exploration Habitat

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I. Introduction

In order to enable long term habitation on planetary surfaces, such as Mars, a means of sustainable food production must be developed. Currently, and historically, the sole method of food provision for space missions is to bring stored stabilized food from Earth for the entire mission duration. While cost effective for short missions, and requiring little hardware other than packaging, this method of food provision is not ideal for long term or permanent residence in space. Thermostabilized and dehydrated food can quickly become unappetizing and has a limited shelf life. Just as on Earth, biological food production must occur to create a sustainable habitat, although biological systems such as plants could require a large amount of overhead mass, volume, power, and crew time to create a constant and usable food supply.

The MarsOASIS system was designed as a proposed solution to some of the scientific and engineering challenges of growing plants for food on Mars. The requirements for this design are based on the constraints posed by the external Martian environment as well as the needs of the crops throughout their growth cycle. This paper describes the conceptual design for this Mars based crop production system, as well as the design of a reduced-scope laboratory prototype built to demonstrate innovative features. Continued research and development of the MarsOASIS system will help answer key questions as precursors to the successful deployment and operation of a crop producing greenhouse on Mars.

II. Motivation

Remote crop production and bioregenerative technology research is ongoing in institutions such as NASA, the Mars Society, Oklahoma State University, Texas A&M University, and Arizona State University.[1] Reference 1 provides an overview of plant cultivation systems that have been developed over the last 40 years and flown on the Salyut and Mir Space Stations, the Space Shuttle, and the International Space Station (ISS).[1] Most recently, NASA launched the VEGGIE Food Production System, to investigate a means to provide supplemental food for the crew on the International Space Station. This system is the first of its kind, designed for food production rather than plant research in microgravity. It consists of a collapsible bellows enclosure to maintain relative humidity, an light-emitting diode (LED) lighting panel, and a root mat that provides passive nutrient delivery.[1] The Prototype Lunar Greenhouse (LGH) built by the University of Arizona Controlled Environment Agriculture Center is a closed greenhouse that can support the growth of a variety of crops.[2] The LGH demonstrates feasibility for inflatable structures on the lunar surface, as well as critical crop life support systems including nutrient delivery and artificial lighting.

The challenges of growing plants on Mars include reduced gravity (1/3g), extreme and rapidly swinging surface temperatures (typically below freezing), low atmospheric pressure, lack of ozone protection from ultraviolet sunlight, lack of a magnetic field, increased radiation exposure, dust storms that block sunlight, and high speed winds. However, the Mars surface also has features that are conducive to plant growth, such as a CO_2 enriched atmosphere and solar radiation levels that are comparable to those on Earth. While crops have been grown in space/microgravity before, they have not been grown on the surface of another planet. A Mars greenhouse must perform reliably and efficiently in this environment, while producing plants that have a high edible crop yield. Before flight qualification, Mars crop production system technology must be thoroughly tested and validated in the closest relevant operating environment.

With technology development and validation in mind, a team of 13 students at the University of Colorado at Boulder (CU) was selected as one of five university teams from around the country to participate in the National Space Grant Foundation sponsored eXploration Habitat (X-Hab) Academic Innovation Challenge for the 2014-2015 academic year. The innovation challenge was to develop a concept and a prototype for a pre-deployable, autonomous Mars greenhouse for crop production technology and system research. The proposed mission scenario has the system being sent prior to a crewed mission to Mars in order to test various aspects of plant growth, as well as the reliability and control of the system. The conceptual design completed by the MarsOASIS team aims to understand the necessary constraints and capabilities of an autonomous greenhouse on the Martian surface, including the subsystems needed to support it, protection from the harsh environment, and innovative features that can make an autonomous greenhouse more feasible for future space missions. A reduced-scope prototype has also been built in order to test the higher risk but necessary features of such a system in a laboratory environment, such as a novel hybrid lighting system, water recycling, and autonomous monitoring and control with remote operation capabilities. The MarsOASIS system is complementary to other bio-regenerative research efforts, such as the LGH built by the University of Arizona, which serves to refine multi-crop mass and energy models which could be used by a Mars crop production system at a scale to support multiple crew members. While not a direct continuation, this project builds upon previous work by University of Colorado students in the X-Hab program involving unmanned gardening and plant growth systems for spacecraft food provision. The technology improvements and innovations developed by MarsOASIS will help address many of the challenges of implementing these systems on other bodies in the solar system.

III. Conceptual Design

A. Requirements

In order to develop the conceptual system design and prototype, the MarsOASIS team defined functional objectives, system level requirements, and assumptions constraining the scope of the system. These requirements and assumptions allowed the OASIS team to better design the system around the most important features, including autonomy and self-sustainability.

Functional Objectives

1) Germinate plant seeds on the Martian surface
2) Grow plant seedlings into mature plants
3) Maintain plant health without human presence until ready for harvest

System Level Requirements

1) Allow for remote control system activation and seed germination
2) Provide the necessary nutrients, light, water, conducive growth environment, and power required for germination and seedling growth
3) Protect the plants and the system hardware from external environmental hazards
4) Utilize autonomous control during normal operation and a teleoperable override when desired or necessary, for managing environmental parameters and consumable resources
5) Ensure that the mature plants are edible and materials are food-grade

Assumptions and Rationale

1) *The greenhouse will not incorporate a means of delivery or deployment to the Martian surface:* Since this design challenge is focused on the crop production system design, the team did not address the spacecraft and deployment systems that would be required to deliver the system to the surface.
2) *The seeds survive transport to the Martian surface:* The prevention of seed germination on the way to Mars would likely impose requirements on the spacecraft and on seed packaging. It also may entail internal system safeguards to prevent the unintentional release of water into the growing area. Though seed hibernation or survival during transport to the Martian surface must be resolved in this operational scenario, it was determined to be outside of the scope of this conceptual design.
3) *The system will be self-powered:* Supplemental spacecraft power was assumed unavailable, such that the greenhouse can operate independently.
4) *The subject plant will be Outredgeous lettuce:* System design requirements were based on a crop of Outredgeous lettuce because it is fast growing, requires little to no maintenance, allows for continuous harvest, has acceptable nutritional content, and has been grown previously in space.
5) *The plant growth area will be* $1m^2$*:* This is the area needed to provide two salads per day for four crew members.
6) *The system will provide support for the plant from germination up until, but not through, harvest:* Harvest and re-planting were determined to be beyond this project’s scope. It was assumed that the human crew would arrive after greenhouse deployment to harvest the crop, and the design does not preclude access for harvest.
7) *The system will not be concerned with replanting for multiple life cycles:* This feature was also considered to be out of the initial concept scope, however, it will be a consideration for future design enhancements.
8) *The telemetry system will rely on external orbiters and/or landers:* In order to communicate reliably with Earth, it was assumed that spacecraft communication systems would be available in orbit or on the surface, such that a self-contained high power communication system would not be needed.

B. Functional Overview

MarsOASIS includes seven sub-systems to achieve the above requirements: Structure, Nutrient and Water Management, Atmospheric Management, Lighting, Thermal Control, Command and Control, and Communications. The structural subsystem encloses the system volume and mass, while providing protection from environmental hazards. The nutrient and water management subsystem manages the water loop, including the provision of water and nutrients to the plants. The atmospheric management subsystem controls the atmospheric composition of the sealed volume and is responsible for providing the plants with carbon dioxide, removing excess oxygen from the atmosphere, maintaining the relative humidity, and supplementing the atmosphere with inert gas to maintain the desired total pressure. The lighting subsystem ensures that the intensity and spectrum of photosynthetically active radiation (PAR) is within the required range for plant growth. The thermal control subsystem provides heating, cooling, and insulation to maintain ideal temperature ranges. The command and control subsystem enables the autonomous environmental control. It uses a suite of sensors to continuously measure environmental parameters, and then a control algorithm to determine the necessary actions that the system must take in order to maintain plant health. Commands are sent to actuated components in order to execute those actions. The communications subsystem enables teleoperation by displaying system health data on a remote user interface, allowing remote users to send additional commands, and then passing those commands to the onboard processor to carry out. Finally, a power subsystem stores and distributes required power.

C. Martian Environment

The Martian environment is harsh and has very different conditions than Earth. Its temperatures are typically below freezing and the low total atmospheric pressure (~600Pa) is around 0.6% of Earth's mean sea level pressure.[3] Ozone is negligible in the thin atmosphere, allowing ultraviolet rays to pass through to the surface unattenuated. Any biological system on the planet therefore needs protection against harmful UV-C rays. Similarly, Mars does not have a global magnetic field due to the lack of an internal dynamo; electronic and biological systems are at risk due to radiation hazards. Carbon dioxide is abundant in the atmosphere, which could prove valuable for growing plants and for CO_2 reduction systems. The surface of Mars can undergo rapid temperature swings between night and day, leading to the formation of long-lasting dust storms, sometimes on a global scale. Dust storms present important design considerations for surface spacecraft: the structure must be able to withstand high-speed winds, sufficient power must be stored to endure a storm with degraded solar access, and the system must be able to prevent dust accumulation and abrasion on the external structure. Thermal control systems must be powerful enough to operate over a wide range of temperatures. Though Mars is located at ~1.4AU, the amount of solar radiation that reaches the surface is comparable to that of Earth because the Martian atmosphere is much thinner. Other technologies, such as radioisotope thermal generators or solar cells, can also be considered for power generation. The acceleration due to gravity is $3.7\ m/s^2$, reducing loads on the system structure.

The MarsOASIS design team selected Gale Crater (5.4°S, 137.8°E) as the landing site for its Martian Greenhouse Concept.[4] Gale Crater is home to the Curiosity Rover and therefore a significant amount of environmental data is available. Located near the equator, the crater has a small temperature variance (-75°C to -2°C) and imposes less stringent requirements on thermal design. This location also provides light cycles nearly equivalent to light cycles on Earth. Gale Crater is a feasible destination for future human missions as it is relatively flat (reducing risk of landing) and it is scientifically interesting.

D. Sustainability

Crop production on the Martian surface presents a unique set of challenges, namely that the expansive distance from Earth increases transport time to Mars and the feasibility of frequent resupply missions. Therefore, the MarsOASIS conceptual greenhouse design emphasizes sustainability, including in situ resource utilization (ISRU), regenerable technologies, and closed loop consumable cycles.

With the exception of in situ resources utilized, all consumables must be deployed with the system and recycled for continued use. These consumables are water, nutrient solution, pH control, growth medium, inert gas (N_2) and a priming volume of carbon dioxide. The chief drivers of the amount of each resource are the plant growth area, type of plant, number of plants, and growth cycle duration.

A model was developed to account for the location and phase of water at various points in the growth cycle. There must be a sufficient volume of liquid water in the system to facilitate nutrient conditioning to last between one and three days at a time. Water is 'lost,' that is, rendered unusable for conditioning, in the saturation of the growth medium, the humidity of the local atmosphere, residuals in the plumbing, leakage to the external environment, and in the plants themselves. A conservative estimate of 4000 ml m^{-2} day^{-1} was made for expected plant evapotranspiration.[5]

The closed water loop design utilizes a continuous drip and recovery system. In this system, nutrient-rich water is pumped from the main mixing tank to the growing bed. A drip manifold then passes the fluid to drip lines which distribute the fluid through the growing bed. Over flow is directed down through the growing bed and back into the mixing tank below. The growth medium is a soil-less mixture that acts as a hydroponic buffer, allowing for non-continuous watering. The nutrient solution is a two-part mixture following the commonly used Hoagland's formula.[6] The system must begin with enough solution to process every liter of water that is recycled over the length of the growth cycle, lasting approximately 30 days. Storage volume is reduced by holding the solution at a higher concentration and diluting it to the appropriate concentration when the water is conditioned. The amount of pH-altering solution is also determined by this method.

Relative humidity control is also incorporated into the water loop. To achieve de-humidification, a heat exchanger will be located external to the sealed greenhouse growing volume and make use of the cold Martian environment. A pump will direct air over a cooling coil located internal to the greenhouse. Moisture in the air will then be condensed, collected, and sent to the primary water storage tank for recycling. Relative humidity can be increased by increasing the internal greenhouse temperature, leading to increased transpiration and evaporation rates within the system. If further testing reveals a need for additional humidification capabilities, a fogging system could be used to add water content to the atmosphere.

The atmosphere revitalization system was also designed with the focus of consumable recycling and in situ resource utilization. In order to reduce the amount of consumables required to maintain the greenhouse atmosphere composition, a total atmospheric pressure for the greenhouse was selected to be 35 kPa. This total pressure accommodates a partial pressure of O_2 that will maintain healthy plant growth (>10 kPa) but not exceed O_2 concentration limits for fire risk (< 30%).[3,7] Additionally, operations at a low total pressure will reduce leak rates.

Lettuce plants consume approximately 10.7 g CO_2 m^{-2} day^{-1} and grow best under sustained CO_2 partial pressures of around 0.12 kPa, therefore necessitating CO_2 provision for plant growth.[8] Since the Martian atmosphere consists of approximately 95% CO_2, it is an excellent, unlimited source of in situ CO_2. However, the Martian atmosphere also contains high levels of dust that must be filtered prior to incorporation into the greenhouse atmosphere. Additionally, the Martian atmosphere has a low total pressure of approximately 0.6 kPa. Typical filter systems would cause the low atmospheric pressure decrease to a level close to vacuum. Therefore, a filter with high particle capture abilities and associated low pressure drop should be selected. A fan will pull the CO_2-rich Martian atmosphere through the filter and send it to a compressor in order to increase the pressure of the CO_2 to the partial pressure utilized within the greenhouse atmosphere.[9] Assuming a human habitat with a CO_2 reduction system exists near the greenhouse, a portion of the concentrated CO_2 from that system could be used to replenish consumed CO_2 inside the greenhouse.

Lettuce plants produce approximately 7.78 g O_2 m^{-2} day^{-1}, which needs to be removed from the sealed growing volume.[10] Regenerable O_2 removal technology was selected that utilizes molecular sieve beds and pressure swing adsorption (PSA) and desorption cycles. 13X and 5A zeolites have a high gas species selectivity for N_2 and CO_2, respectively, and heritage on past space missions.[10] In this process, two canisters contain the zeolite molecular sieves. Dry air is passed through one canister, which selectively adsorbs N_2 and CO_2, while O_2 passes through the column to a storage tank. Once the active adsorption column is saturated, the adsorbed N_2 and CO_2 are desorbed and exhausted back into the growth volume by exposure of the canister to low pressures. While the first column is desorbed, the second takes over the adsorption process via PSA cycles.[11] The stored, excess O_2 could then be used by future human inhabitants.

Finally, a hybrid lighting system will be employed. Natural sunlight will be the primary light source for the system and will be supplemented with artificial light, specifically red and blue LEDs within the growing volume. The LEDs will be utilized during dust storms when access to natural light is limited and also to enhance the light spectrum for plant growth. The red and blue LED spectrum was selected over white light to enhance the production of antioxidants in the plants and to limit wasted power on unused wavelengths of the full white light spectrum.[12]

E. Autonomy

The conceptual design of the system must include the capability to remotely command initial germination, actively monitor and control subsystems to adjust growth parameters autonomously, provide a graphical visualization of the monitored data to users and operators on Earth, and provide override capabilities to authorized users.

Upon receipt of the command to initiate germination, the system will actuate pumps to begin the flow of water into the growth bed. The processor will then run algorithms to monitor environmental parameters and execute scripts to actuate components as needed to maintain the ideal growth environment for the greenhouse. Monitoring growth parameters will occur with a sensor suite that includes cameras for visualization and image processing. Data from the system will be logged and then telemetered to Earth. The processed data will be compressed prior to transmission from Mars. The data will uplink to Mars orbiters that will then communicate with Earth via the Deep Space Network (DSN). This process is visually depicted in Fig. 1.

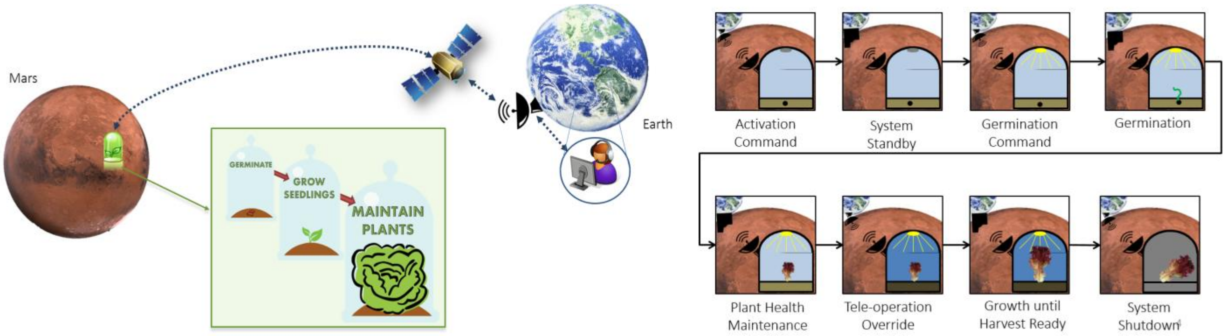

Figure 1. Autonomous Remote Control Concept of Operations.

To maximize the frequency at which data will be received on Earth, more than one orbiter will be used to relay data to the DSN. Telemetry was not a focus area for MarsOASIS, therefore it would need to be further detailed for future mission designs. On Earth, users including the general public, scientists, engineers, and system operators at NASA will have access to greenhouse data through a secure website. The website will have different levels of information and teleoperation functionality available based on user type.[13]

F. Structural Design

The structural design for the MarsOASIS concept greenhouse has several design drivers: it must hold pressure, have low mass, and be partially translucent. These design requirements led to the selection of the pill-shaped design shown in Fig. 2. With this 'pill-shaped' design, the structure can withstand large pressure differentials between its internal atmosphere and the external Martian atmosphere using only a thin shell. The top half of the structure was required to be translucent to accommodate for in situ use of natural light. Polycarbonate was chosen for the upper structural shell due to its low density, high transmittance, and extensive space heritage. Polyetheretherketone (PEEK) was selected for the bottom half of the structure also due to its low density, high strength, and space heritage. Within the structure, there are two main inner supporting structures: the growth platform and the structural ribs, as shown in Fig. 2. The growth platform provides support for any sensors or mechanical apparatuses required for direct support of the plants. It also provides separation of the lower, subsystem volume, and the upper growth volume. The structural ribs follow the contour of the lower shell and provide mount points for all subsystem hardware including liquid and gas tanks, plumbing and electronics.

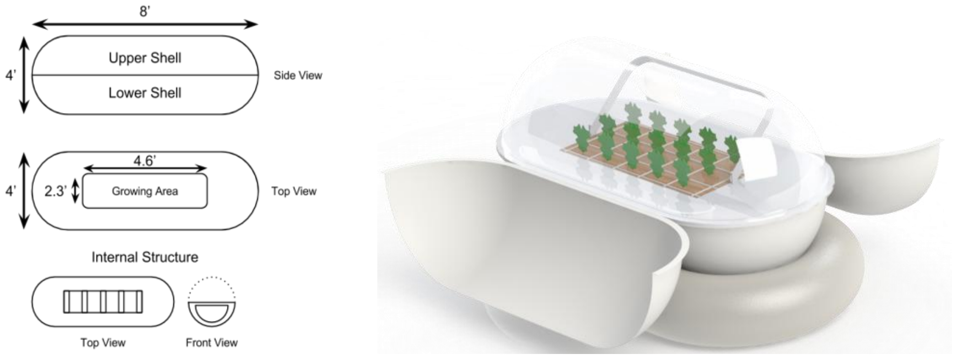

Figure 2. Structural ribs and shell (left) and CAD structural concept (right). *The structural ribs are depicted in the lower 'Top View' drawing.*

On the outside of the structure, two ‘clam shell’ style lids provide thermal insulation at night while the translucence of the polycarbonate is irrelevant. Additionally, the lids can be closed in the event of a dust storm to prevent degradation of the polycarbonate transmittance. The inner surfaces of the lid are lined with flexible photovoltaic panels to collect solar energy while open and provide the main source of power for the greenhouse. The entire structure sits on an inflatable cushion which is deployed upon landing. The cushion design allows for minimal stow volume during transit and can also act as an external gas storage tank either for oxygen generated by the plant or as a staging area for carbon dioxide taken from the Martian atmosphere. Additionally, the cushion allows for a sturdy interface between the greenhouse and the ground on uneven terrain. A preliminary analysis was conducted based on the shape and mass of the greenhouse, slope of the terrain at the chosen location, and expected wind speeds and found that there is no risk of the greenhouse tilting.

G. Risk Assessment and Failure Modes

A risk assessment of the conceptual MarsOASIS design illuminated many potential failure modes or hazards that could lead to decreased performance. Some of the more severe risks identified include the following:

Wilting: Given that communication between MarsOASIS and the Earth ground station may be limited to a short period within a day, there is the potential that plant wilting or other emergency conditions may occur, compromising the crop before the ground operator can detect or react to the situation. The system will process images of plants to determine whether wilting is occurring, convert to emergency mode, and send an emergency signal to the Earth ground station through the deep space network if possible. Though the inability to react immediately to degraded environmental parameters presents a threat to the crop, reliable telemetered communication with Mars is currently unavailable technology. The MarsOASIS design assumes that multiple orbiters could be available to increase communication capability.

Condensation on Electrical Components: Given that water vapor in the atmosphere may condense onto exposed electrical components there is the potential for a short circuit, resulting in electrical system degradation or failure. Component exposure to the atmosphere should be minimized and exposed components will be water resistant/proof.

Light Degradation Due to Dust Accumulation or Abrasion: Given that dust storms can occur over large distances for days or weeks at a time on Mars, dust can accumulate on the dome or abrade the system. Therefore, there is the potential for sun transmission to be reduced below tolerable levels for survival and for solar power generation to become degraded. The clam shell lid will close during periods of high winds and/or low light, allowing artificial light to take over during dust storms and protecting solar panels from degradation. Stored power is expected to last through the average length dust storm, but may not be able to provide enough power for artificial lighting for a storm that lasts longer than two months.

Failure of Lid Closure Due to Dust Infiltration: Given that the clam shell lid will be open during the day to collect light, there is the potential that dust can infiltrate the hinge, leading to mechanical failure of the lid to close and potential crop failure due to low nighttime temperatures. The clam shell lid design would incorporate hermetically sealed joints.

Radiation Exposure: Given that there is increased radiation (solar and galactic) on the Martian surface compared with that on Earth, there is potential for plant damage due to radiation exposure. However, this risk is considered acceptable since the expected radiation exposure over a 100 day mission is ~20 REM, well under plant tolerance for exposure to >1000 REM.[14]

Salt Buildup in Condenser or Plumbing: Given that salt deposits from dissolved solids in the nutrient solution could build up in the water vapor condenser, water pumps, growth medium, and plumbing to the water reservoir, there is the potential for clogs to degrade flow rates. A system running for extended periods of time or for multiple life cycles should flush its water lines with fresh water during periodic system maintenance.

Internal Fluid Leak: Given that fluid will be traveling through the water management system under pressure, there is the potential that water could leak from the water management system resulting in loss of total water available for plant uptake and potential damage to other system components. Components must be chosen and tested to withstand expected water pressures and minimize likelihood of leaks.

Fungal Infections at Plant Roots (Root Rot): Given that nutrient enriched water will be recycled and recirculated through the water reservoir, there is the potential for fungal spores to grow and infect plant roots, resulting in degraded plant growth or crop failure. The root medium must be continuously aerated and the water circulated. Also, UV filtration is used to remove or kill spores or other pathogens.

Pump or Valve Failure: Given that components with mechanisms or moving parts are at a higher risk of failure in the extreme temperatures and pressures and reduced gravity of the Martian environment, there is the potential for pump or valve failure to occur resulting in loss of water at the plant roots. Design redundancy should be considered for these critical mechanical components.

H. Engineering Challenges

The following engineering challenges that were not addressed in the current concept could be considered in future development and enhancement of the MarsOASIS system and should be considered prior to any Mars-based agricultural production system.

1) *Germination Delay and Seed Care:* Given that seeds will be transported within the MCLSS from Earth to Mars and the MCLSS could be on the Martian surface for some period of time prior to germination there is the potential for germination to begin prematurely. Methods of keeping the seeds dormant and dry will be required.

2) *Decreasing System Costs:* The challenge of space crop production system design is to maximize the production of edible biomass while minimizing launch and use costs, such as power, mass, volume, consumables, and crew time. To this end, the MarsOASIS conceptual design incorporates the use of in situ CO_2 and sunlight, storage of concentrated nutrient solution, a water recycling loop, and autonomous control. However, further analysis of the total expected operational costs, volume, and mass is needed to estimate the Equivalent System Mass (ESM) of the proposed design.

3) *Communication Lags:* The MarsOASIS design assumes the availability of orbiters or landers to transmit data back and forth from an Earth ground station. However there will still be ~15 minute delays between the transmission and receipt of data. This delay may prevent an operator from responding quickly to a system failure. Future performance characterization of the prototype will include simulated communication time lags to assess the impact of delays on performance and the ability to recover the system under various failure modes.

4) *Dust build-up:* Given that in situ CO_2 will be extracted from the Martian atmosphere into the system, there is the potential that the compressor system will be abraded by dust, reducing performance or causing system failure. This was mitigated in the design by the use of a Filtrete filter but future work should consider additional design features for mitigation. Also, there is the potential for reduction in light transmission due to dust build-up on the dome, despite clam shell lid closure during dust storms. Future studies of system reliability should include analysis of the expected dust accumulation on the dome and on the photovoltaic panels.

5) *Long Term Reliability and Operation:* Future design iterations will assess the additional costs of operating the system over multiple growth cycles, including the replacement or repair of parts such as filters and pumps, sensor calibration methods and schedule, sanitation, harvesting, and re-planting. The expected man-hours for system operation and maintenance should be included in reliability studies and operational cost estimates.

6) *Low pressure operation:* Given the low pressure atmosphere on Mars, the MarsOASIS system is designed to operate under reduced internal pressure (35 kPa) in order to improve structural integrity and prevent gas leakage. It is widely accepted that reduced atmospheric pressure results in higher evapotranspiration rates, due to increased gas diffusion.[15] However, further studies are needed to define the response of crops to changes in total atmospheric pressure and refine operational requirements and control systems.

7) *Reduced gravity:* The effects of reduced gravity (1/3g) on system performance are unknown and will need to be assessed in future design efforts. Reduced gravity may increase condensation on the dome, disrupt uniformity of water dispersion throughout the growth medium, or otherwise degrade the performance of the water recycling and humidity control systems.

8) *Control Strategy Optimization:* The current MarsOASIS control strategy maintains environmental conditions within preset ranges, or limits. However, it is likely that dynamic control strategies that determine target conditions based on current system state measurements would allow improved performance and reliability. Future laboratory research with the prototype will compare the performance of various autonomous control algorithms in an effort to maximize plant biomass production, while reducing consumables and power usage.

9) *Accessibility for Harvest and Maintenance:* Operational considerations must be made for accessing the system during harvest, re-planting and maintenance. The system could be brought into a pressurized environment or otherwise integrated into the crew habitat. The chosen means of accessing and maintaining the system by the crew may impose additional mechanical design requirements.

10) *Algae Buildup on Dome*: Given that MCLSS atmospheric conditions are conducive to algal growth, there is the potential for algae to grow and accumulate on the transparent dome or artificial lighting system, reducing or blocking light transmission from the sun or artificial lighting system. Future design iterations will assess the magnitude of this risk and consider potential means for preventing algae growth.

IV. Concept to Prototype

This research explores two distinct but related thrust areas: a conceptual design and a reduced-scope prototype. The conceptual design examines the engineering challenges of a mission to operate a greenhouse on the surface of Mars. It outlines science questions, engineering challenges, mission hardware, and system functionality. The purpose of the prototype is to demonstrate key technologies and solutions in advance of an actual mission. The prototype will demonstrate innovative approaches to a subset of engineering challenges, identify risks, and integrate all desired functionality into a single package. The unit itself will also serve as a platform for future research within the University of Colorado Bioastronautics group.

The extent to which the prototype is de-scoped from the conceptual design is driven by the aim to reproduce only those things that are critical to demonstrating the core focus areas: autonomous control, teleoperation, resource recycling, and in situ resource utilization. Areas specifically excluded from consideration are radiation tolerance, space qualified hardware, flight readiness, power supply, and radio communications. Other factors that influence prototype design are budget, academic schedule, sourcing and fabrication abilities, safety concerns, and the terrestrial environment.

Since the conceptual design calls for environmental conditions comparable to Earth standard temperature and pressure (STP), the prototype need not be a capsular pressure vessel; instead, the structure is in the shape of an unsealed rectangular base beneath a sealed but unpressurized semicircular enclosed volume. Similarly, thermal insulation and the clam shell lid are not required under lab conditions. In addition, the material of the dome is acrylic instead of polycarbonate. Finally, the growing volume and number of plants are scaled down to accommodate a 0.61 m (2 ft.) diameter growth area.

Owing to safety concerns, the storage and usage of pure oxygen were modified in the prototype. Instead of being stored for future use, oxygen produced by the plants is safely vented into the lab environment after output levels are measured. For the same reason, the dissolved oxygen aeration system is fed from ambient air instead of an O_2 supply.

Power generation, power storage, and radio communications are essential parts of any space mission. However, since these functions are not among the core focus areas of autonomy and sustainability, they were de-scoped for the prototype. Solar energy and communications systems would utilize existing space based technology, and their inclusion would not add novelty to the prototype. In lieu of photovoltaics and batteries, the system utilizes a standard 120 VAC wall outlet. Adopting a ‘black box’ communication model, antenna designs and data link budgets were also excluded.

Although the favorable conditions of the terrestrial environment allow for the reduction in prototype scope in some areas, it is important to simulate certain aspects of the Martian environment in order to demonstrate the project goals. For example, the high CO_2 content of the Martian atmosphere is simulated with an external tank supply to emulate in situ resource utilization. For the same reason, Martian lighting intensity, spectrum, and duration is simulated with LEDs. UV light for bio-filtering is artificially generated with a commercial filtration package. The system also allows for simulated radio communication lag and blackout periods that would be encountered in an Earth-Mars system.

The remainder of this paper will provide detailed descriptions of the system prototype.

V. Prototype

The system prototype was constructed to gauge the difficulty of operating a closed plant growth system while recycling resources and monitoring plant health autonomously. Specifically, the natural/artificial hybrid lighting and sensing method, closed loop water recycling approach, full system autonomy, and human-interrupt elements from the conceptual design were designed and constructed.

In the prototype, Nutrient and Water Management is provided with a hydroponic ebb and flow system and a thermally controlled, recycled water loop. Thermal control in the atmosphere is provided by the chilling and heating of water in the main storage tank, and actively through humidity control. The Atmospheric Management system will maintain the desired atmospheric composition inside of the sealed growth volume with gaseous N_2 from external storage tanks. CO_2 will be injected into the sealed chamber from external storage tanks as well. Excess O_2 produced by the plants will be removed by passing air from the growth volume through a commercial medical oxygen concentrator, which separates oxygen from the other atmosphere constituents using a molecular sieve, PSA system. A stream of approximately 93% O_2 will then be vented from the concentrator to the lab and the O_2-depleted air will be directed back to the growing volume. The Atmospheric Management system will also provide humidity control by adapting a commercial humidifier and dehumidifier to the system. The Command and Control system processes sensor data and actuates components through an onboard data processing unit. The Communications System displays system data for a remote user through a web-based Graphical User Interface, allowing the user to then teleoperate the system. The system structure includes a low leak rate vessel to contain the controlled atmosphere, a transparent dome to allow transmission of Mars simulated in situ light, and also a rotating bracket under the transparent dome with mounted LEDs and a movable, high-definition camera for monitoring plant health.

A. Prototype Environment

Unlike the conceptual design, the MarsOASIS prototype will operate in a pseudo-controlled laboratory environment. The University of Colorado Bioastronautics lab will be at a constant room temperature of 22°C ± 3°C (72°F ± 5°F), average relative humidity of 28%, and ambient pressure of 84 kPa. In order to better simulate the natural Martian lighting, a broad spectrum LED lighting system has been loaned to the project by AcroOptics. The AcroOptics CRAVE 24 provides light with a customizable spectrum made possible by a combination of UV, white, amber, blue, and red LEDs. The extensive software system made for the CRAVE 24 allows the user to program the light cycle daily for up to a 500 day duration. A custom firmware upgrade designed exclusively for the MarsOASIS project allows the day length to be adjusted to that of the Martian equator. This firmware also allows the MarsOASIS team to create a high fidelity Martian light simulation including correct spectrum, light cycle and dawn/dusk fades. The incident lighting to the system will be isolated using black-out curtains to eliminate parasitic light from other lab users.

B. Prototype Design

1. Structural and Mechanical Design

The prototype structure consists of a sealed upper growing volume supported by a frame that houses most of the subsystem components and is open to the ambient atmosphere, as depicted in Fig. 3. Air-tight feed-throughs provide the subsystem components access to the sealed growing volume. The dimensions of the greenhouse are 1.22 m by 1.22 m by 1.22 m (4 ft. by 4 ft. by 4 ft.).

a. Structural Support and Integration

The support structure and housing for a majority of the subsystem components is composed of an open 80/20 aluminum frame. The use of 80/20 allows for rapid and reconfigurable construction, since all components can be secured to the main structure either by integration into the 80/20 through its integral T-slots or using straps. The system is supported by eight caster wheels, each with a capacity of 68 kg (150 lbs.), providing mobility and strength to support the heavy water supply. The four outer casters each have integrated brakes which keep the structure from moving during testing.

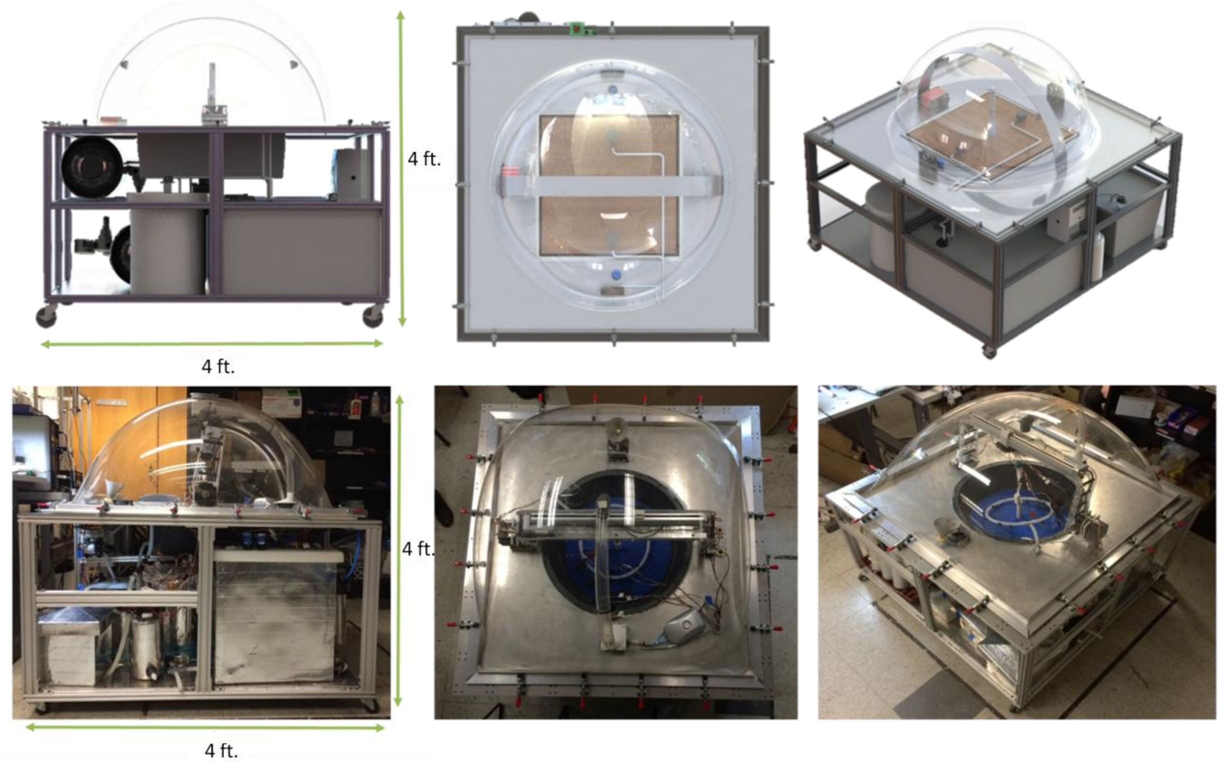

Figure 3. Prototype CAD (upper) and actual (lower) structure.

b. Growth Volume Seal

The growth volume utilizes two main seals to ensure that the system is air-tight. The growth bed is sealed around its perimeter using pressure washers, which seal around each bolt, and silicone gel to seal the interface between the growth bed and the structure. The dome is also sealed around its perimeter using a layer of polyethylene between the edge of the dome and the metal surface of the support structure. The layer is compressed using toggle clamps to provide pressure and rigid aluminum L-brackets to evenly distribute the pressure over the seal. Toggle clamps are used to provide quick and easy placement or removal of the dome. All feed-throughs from the sealed growth volume to the subsystem components located below have been made air-tight using compression cord grips and silicone.

A manometer is installed for pressure relief of the sealed growth volume. It is currently set to 0.1 psi but is adjustable. Additionally, the manometer is sized so that if all the air intakes to the growth volume are opened at the highest setting, the manometer will be able to vent the gas at the same flow rate, making it physically impossible to pressurize the growth volume.

c. System Visualization

A camera with two degrees of freedom is mounted inside the growth. The bracket holding the camera is attached to stepper motors so that it can be positioned at any angle between 0 and 180° relative to the horizontal. The camera is mounted on a linear actuator that runs the entire length of the bracket, allowing for 0.5 m (20 in.) translation. Therefore, the growth area can be viewed at any position, from any angle, with the ability to stow the camera out of the way of the external light source and LEDs when not in use.

d. Hybrid Lighting

To accommodate the hybrid lighting system, MarsOASIS makes use of an acrylic dome, which allows exposure of the Outredgeous lettuce to an external light source with a nominal transmittance of +90%, in addition to LED lighting located internal to the growing volume. The white LEDs are mounted to the underside of the camera bracket, therefore allowing LED light to reach all sides of the growing bed via the 180° rotation of the camera bracket. Additionally, having mobile lighting allows for the plants to get the maximum amount of natural light by maneuvering the bracket so it does not cast a shadow on the growth area based on the position of the sun in the Martian sky. The bracket can adjust the light position based on plant growth to sustain uniform growth of all plants within the chamber.

2. *Atmospheric Management*

The atmospheric management system consists of components located both interior and exterior to the sealed growth volume. The fogging nozzle, dehumidification system air pump, and circulation fans reside within the growth volume. The gas tanks, solenoids, valves, oxygen concentrator, dehumidification system, and pump to feed the fogging nozzle are external to the growth volume. The bulk of the components are located outside the sealed volume in order to minimize the amount of volume that must be sealed as well as to allow accessibility in case of maintenance. All flow lines utilize clear, sanitary PVC flexible tubing, and all components are equipped with barbed and NPT fittings, with metal hose clamps and thread tape, respectively, to ensure air-tight seals. Table 1 details the major component specifications.

Table 1. Atmospheric Management Components.

Component	Dimensions	Input Voltage	Flow rate	Concentration	Outlet Pressure	Internal Pressure
Oxygen Concentrator	18-3/8" W x 26-3/8" H x 14-3/8" D	120VAC	0.5-5 L/min	93%	5 psi ± 0.5 psi (max)	--
Nitrogen Tank	20" H x 7" OD	120VAC (solenoid)	0.5 L/s	>99%	5 psi	1600 psi
Carbon Dioxide Tank	20" H x 7" OD	120VAC (solenoid)	0.5 L/s	>99%	5 psi	700 psi
Dehumidifier	5.7" W x 8.7" H x 5.3" D	120VAC	250 mL/day	--	--	--
Fogging Nozzle	9/16" OD x 15/16" L	12VDC (water pump)	9 mL/s	--	40 psi	--

a. *Oxygen Removal*

The Invacare Platinum Oxygen Concentrator, a commercial of the shelf (COTS) medical oxygen concentrator, was selected to remove oxygen produced by the Outredgeous lettuce from the sealed growth volume. The concentrator is powered by 120 VAC, and operates by pulling air from the growth volume and passing it over a molecular sieve bed that adsorbs N_2. A stream of 93% O_2 is exhausted to the lab at a rate controlled to be within a range of 0.5 - 5L/min. The concentrator utilizes PSA, during which the saturated molecular sieve bed is desorbed and N_2 is returned to the growth volume.

This regenerable technology is an excellent demonstration of the types of systems that will be used on Mars to reduce consumables. A simple air exchange with the lab environment was considered in order to simplify the atmospheric management of the MarsOASIS prototype, but did not support the goal of maintaining a sealed growth volume and was not applicable to the conceptual design. A manual valve is installed as a feed-through into the system; this access port will remain closed for nominal testing, but allows for modified gas compositions to be sent into the growth volume for future testing purposes.

b. *Carbon Dioxide and Inert Gas Provision*

Nitrogen was selected as the inert gas in the growth volume used to replace the removed O_2 and compensate for any leaks. CO_2 and N_2 are both supplied via pressurized tanks, with the CO_2 and N_2 tanks filled to 700 psi and 1600 psi, respectively. The high-pressure tanks are regulated down to the lowest setting, releasing gas into the sealed system at 0-50 psi via solenoid actuators, allowing for fine-tuned control of CO_2 provision to the growth volume and to reduce the risk of system over pressurization. The solenoid actuators are rated up to 250 psi and do not require pressure assistance to activate.

c. Air Circulation

The N_2 and CO_2 intakes to the growth volume are adjacent to one another and located underneath a circulation fan. This fan is a simple computer fan connected directly to an air duct running along the inside surface of the dome to the top of the dome. An elbow directs the flow down to the center of the growth area. Downward airflow reduces temperature gradients through the plant canopy, and the circulation fan ensures the atmosphere is well mixed at a rate of ~1 growth chamber volume/min.

d. Humidity Control

Humidity control is accomplished via dehumidifier and fogging nozzle. The dehumidifier is an Ivation unit that implements the Peltier effect to cool its cold plate and remove water from the atmosphere at a rate of 250 mL/day. Since the unit is located external to the humid growth volume, an Active Aqua air pump is used to pump air out of the growth volume to the unit, increasing the flow rate of humid air over the dehumidifier's cold plates. Dry air is returned to the growth volume, and condensed water is sent to the condensate tank.

The fogging nozzle is an impact nozzle requiring a water pressure of at least 40 psi. This high pressure is supplied with a Kleen Rite water pump. Although rated to fogging specifications, the nozzle produced water droplets large enough to actively condense on the inner surface of the growth volume dome due to the volume's small size. Therefore, a mesh sheet with openings of 0.03 cm (0.012 in.) was placed in a cone shape around the misting nozzle to further atomize the water droplets and reduce this effect.

e. Trace Contaminant Control

BluApple ethylene sorbers of sodium permanganate are placed near the plant canopy. The sorbers adsorb ethylene, a harmful contaminant produced naturally by the plants that can hasten their ripening.

3. Nutrient and Fluid Management

The nutrient and fluid management system provides the plants with water, nutrients, and a root environment for healthy growth. The system is a recycling hydroponic ebb and flow system with a soilless substrate. It contains hardware for nutrient delivery, pH control, water heating and cooling, filtration, and biological contaminant purification.

a. General Operation

Liquid conditioning begins in the 'mixing tank' where nutrients are added to the water. The water is enriched with dissolved oxygen by an air stone bubbling unit and further conditioned to the desired pH value. The conditioned water is then pumped to the growth bed containing the plants and soilless substrate. Most of the water is drained into a collection tank labeled 'leachate'. Some of the water is absorbed by the plant and either remains there or is released into the atmosphere during evapotranspiration. Once the relative humidity rises, the atmospheric system condenses it into liquid form and ultimately deposits it into the leachate tank. From the leachate tank, the liquid is sent through a 1-micron filtration unit, followed by a UV filter that acts as a biocide against microbial contaminants. Finally, the filtered liquid is recycled back into the mixing tank to begin the process again. A full cycle occurs once or twice per day, depending on the maturity of the plant and environmental conditions. Figure 4 illustrates the process.

b. Nutrient Solution

The plant nutrient solution is a composed of two parts kept at high concentrations in separate tanks. During a conditioning operation, the nutrients are dosed into the mixing tank. The first part of the solution is a custom mixture of nitrogen, phosphorous, and potassium in addition to magnesium sulfate ($MgSO_4$). The second part is calcium nitrate ($CaNO_3$). A two-part solution prevents chemical precipitates from forming before the plant can absorb the nutrients. The tanks are also stirred periodically with a recirculating pump. Since electrical conductivity is proportional to salt content, this parameter is measured to estimate the amount of nutrient solution to be added to the mixing tank.

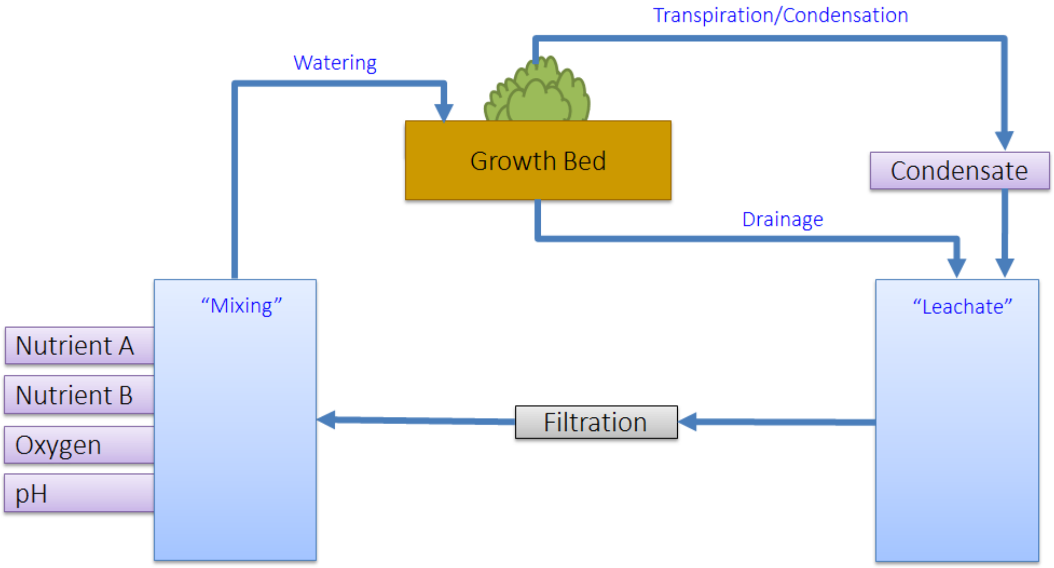

Figure 4. Simplified nutrient and fluid management subsystem diagram. *Blocks represent liquid tanks; arrows represent tubing for liquid movement (except in the case of transpiration/evaporation).*

c. *pH Control*

Ab-initio calculations show pH will increase over time and thus a reduction in pH will be needed to balance the mixture. A diluted solution of nitric acid is dosed into the mixing tank during a conditioning operation. The typical pH range of the solution within the mixing tank is 5.6 – 6. A pH sensor is placed in each the mixing tank and the leachate tank.

d. *Temperature Control*

The temperature of the liquid in the mixing tank is controlled through two COTS units; a compact cartridge-style immersion heater and a thermoelectric aquarium chiller probe. Temperature is maintained between 59°F and 68°F. Temperature sensors are placed in the mixing tank and in the growth bed.

e. *Growth Media*

The primary growth medium substrate (~70%) is made from coco coir. This retains water in the root zone and buffers against quick or dramatic changes in liquid composition and temperate. Small rocks are mixed with the substrate (~20%) to ensure drainage and water flow. The top layer of the mixture (~10%) is seed starting mix that facilitates successful germination.

f. *Watering*

Nutrient conditioned water is delivered to the growth bed through a ring of tubing suspended at the level of the growth medium surface. The tube is implanted with pressure compensated drip nozzles ensuring steady, even flow during a watering operation and uniform saturation of the growth medium mixture. Moisture sensors in the growth bed monitor the volumetric water content by measuring the dielectric constant of the soil.

g. *Filtration*

Filtration is a key element in a recycling system and several filters are present throughout the system. A high-density mesh mat lays on the bottom of the growth bed to prevent the growth media from entering the system through the drain. The drain itself is fitted with a strainer unit that prevents smaller particulates from penetrating. In the event that solid matter from the substrate or the plant enters the liquid lines, a strainer pre-filter is fitted inline before each pump. The main filtration system is a two-part unit. The first part is a 1-micron sediment filter. The second part is a UV light unit that acts as a biocide against microbial contaminants.

4. Electrical Engineering and Software Design

a. Control Logic

The Mars OASIS Control Logic, implemented in Python on a BeagleBone Black microprocessor, allows the system to autonomously control environmental parameters necessary for healthy plant growth, while also allowing remote user interaction with the system. A snapshot of this control logic is shown in the Fig. 5. When the system is first activated (powering on), it will begin an INITIATING mode during which it will autonomously perform system health checks and report system health to the user. If the system appears to be operating properly, it will enter a STANDBY mode, during which it awaits instruction on how to proceed from the user. The user can choose to either *Initiate Germination* or *Auto-operate* or *Teleoperate* through a web-based Graphical User Interface (GUI) that was based on the work of Autoponics' Daniel Zukowski. A snapshot of the GUI is displayed in Fig. 6. If germination is initiated, components are actuated to release conditioned water from storage tanks into the growth medium and begin environmental control of the atmosphere.

After this germination initiation phase, the system will enter an AUTONOMOUS mode, in which growth medium moisture levels are maintained through a *Watering Function* that reads the moisture sensors and initiates the main pump when volumetric water content of the growth medium reaches a certain threshold. CO_2, O_2, and total pressure are controlled through a *Gas Composition Function* by balancing simulated CO_2 input from the Mars atmosphere, O_2 removal by an O_2 concentrator, and N_2 provision; Temperature and Relative Humidity are controlled through a *Vapor Pressure Deficit Function* by active humidification and dehumidification systems. Photosynthetically Active Radiation (PAR) intensity is controlled through a *Lighting Function*. Plant images are taken and stored at regular intervals through a *Time Lapse Function*. Finally, a controlled day/night cycle is maintained through a *Day Cycle Function*. In the snapshot below, an example is given of the *Water Function* control loop. If users choose to change the controlled set point of an environmental parameter, they can do so through the GUI. Also, if users wish to operate system components independently, they may 'pause' autonomous control loop through the GUI, putting the system back into STANDBY mode.

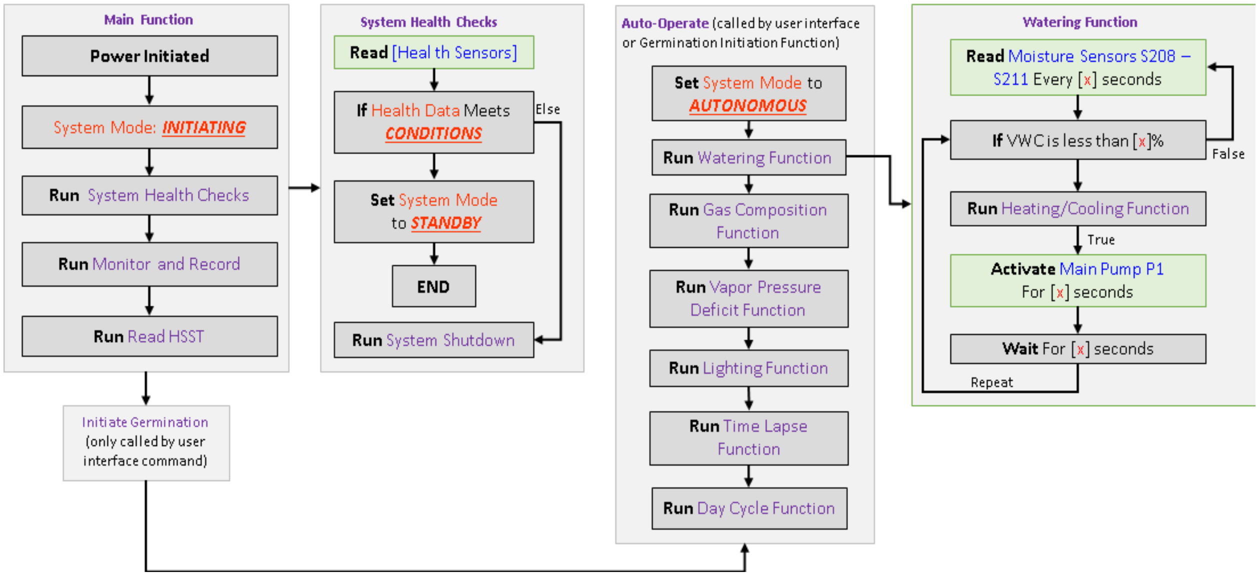

Figure 5. MarsOASIS Control Logic snapshot.

b. Sensor Suite

The MarsOASIS sensor suite is a comprehensive group of 36 sensors listed in Table 2. The system will autonomously activate the necessary hardware to maintain the ideal growth environment for the plants based on the data collected from the sensors. The sensor suite was designed to accommodate sensing of the internal atmosphere, liquid tanks, growth medium, and external atmosphere. The sensor suite interacts with the two BeagleBone Black microprocessors in the system. Control logic algorithms will constantly run, monitoring the system and actuating necessary hardware.

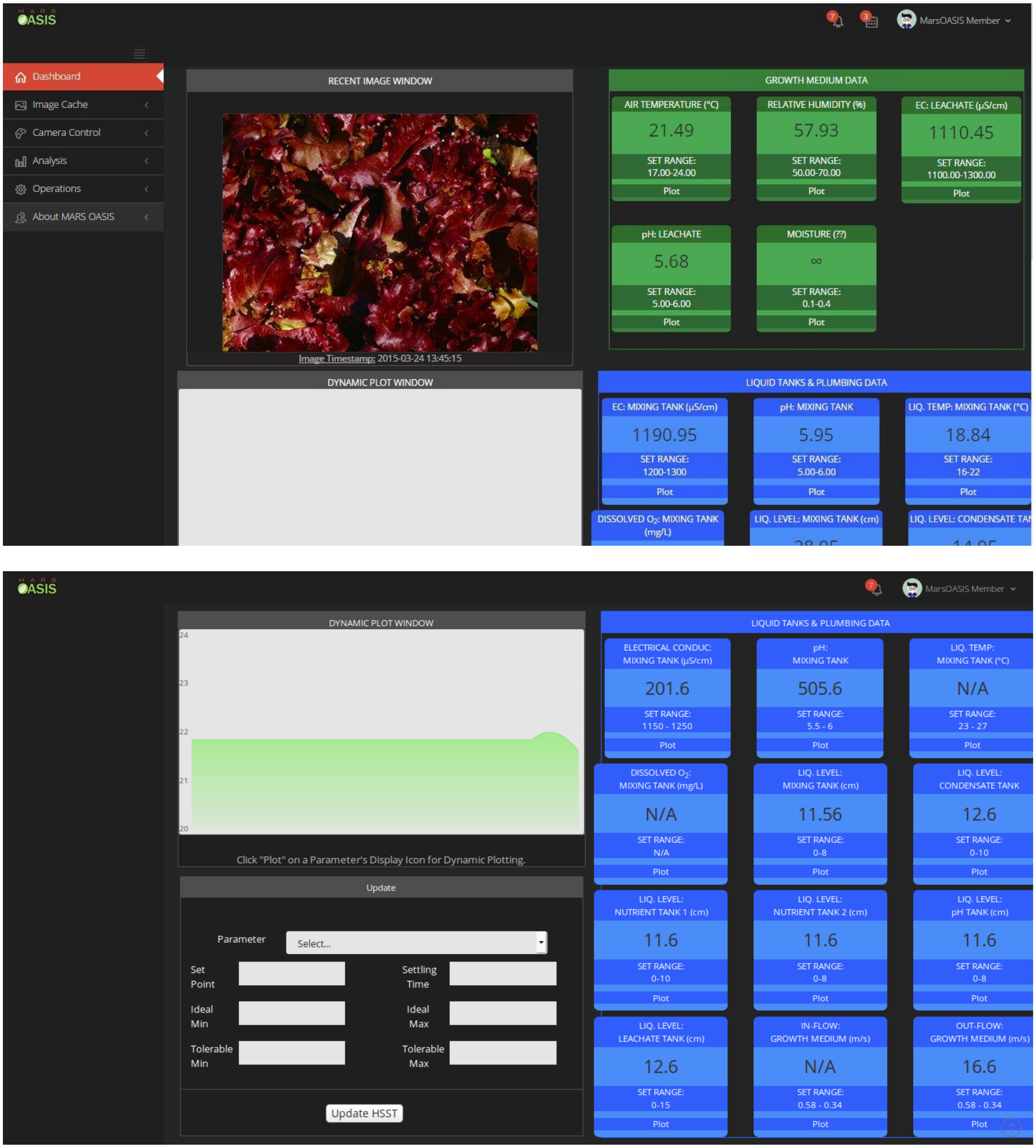

Image Timestamp: 2015-03-24 13:45:15

AIR TEMPERATURE (°C): 21.49 — SET RANGE: 17.00-24.00
RELATIVE HUMIDITY (%): 57.93 — SET RANGE: 50.00-70.00
EC: LEACHATE (μS/cm): 1110.45 — SET RANGE: 1100.00-1300.00
pH: LEACHATE: 5.68 — SET RANGE: 5.00-6.00
MOISTURE (??): ∞ — SET RANGE: 0.1-0.4

EC: MIXING TANK (μS/cm): 1190.95 — SET RANGE: 1200-1300
pH: MIXING TANK: 5.95 — SET RANGE: 5.00-6.00
LIQ. TEMP: MIXING TANK (°C): 18.84 — SET RANGE: 16-22
DISSOLVED O_2: MIXING TANK (mg/L)
LIQ. LEVEL: MIXING TANK (cm)
LIQ. LEVEL: CONDENSATE TAN

Click "Plot" on a Parameter's Display Icon for Dynamic Plotting.

Parameter: Select...
Set Point:
Settling Time:
Ideal Min:
Ideal Max:
Tolerable Min:
Tolerable Max:

ELECTRICAL CONDUC: MIXING TANK (μS/cm): 201.6 — SET RANGE: 1150 - 1250
pH: MIXING TANK: 505.6 — SET RANGE: 5.5 - 6
LIQ. TEMP: MIXING TANK (°C): N/A — SET RANGE: 23 - 27
DISSOLVED O_2: MIXING TANK (mg/L): N/A — SET RANGE: N/A
LIQ. LEVEL: MIXING TANK (cm): 11.56 — SET RANGE: 0-8
LIQ. LEVEL: CONDENSATE TANK: 12.6 — SET RANGE: 0-10
LIQ. LEVEL: NUTRIENT TANK 1 (cm): 11.6 — SET RANGE: 0-10
LIQ. LEVEL: NUTRIENT TANK 2 (cm): 11.6 — SET RANGE: 0-8
LIQ. LEVEL: pH TANK (cm): 11.6 — SET RANGE: 0-8
LIQ. LEVEL: LEACHATE TANK (cm): 12.6 — SET RANGE: 0-15
IN-FLOW: GROWTH MEDIUM (m/s): N/A — SET RANGE: 0.58 - 0.34
OUT-FLOW: GROWTH MEDIUM (m/s): 16.6 — SET RANGE: 0.58 - 0.34

Figure 6. Snapshot of the GUI upper Dashboard (upper) and lower Dashboard (lower) as displayed on the operating computer screen. *The Dashboard includes the most recent image of the plant growth, growth parameter data, and dynamic plotting of growth parameters in addition to the ability to update HSST values.*

Table 2. Mars OASIS Sensor Suite.

Sensor Type	Qty	Function	Units	Range	Required Resolution
EC	2	Electrical Conductivity (Measuring Nutrient Deficit) in Growth Medium & Reservoir	μS-cm-1	3-3000	1
pH	2	pH in Growth Medium & Reservoir	pH	2-12	0.2
Temperature	5	Liquid Temperature in Reservoir (1) & Growth Medium (4)	°C	0-100	1
Moisture	4	Volumetric Water Content in Growth Medium	%	0-50	1
DO Probe	1	Dissolved Oxygen in Mixing Reservoir	mg/L	0-15	0.1
Liquid Level	7	Liquid Level in Mixing, Nutrient, pH, Leachate, & Condensate Tanks	cm	0-40.5	1.25
Flow Meter	2	Water Flow Rate Into & Out of Growth Bed	gpm	0.2-2	0.05
RH/Temp (Air)	3	Internal (2) & External (1) Relative Humidity & Air Temperature	% °C	5-99 -40-80	1 0.2
Total Pressure	2	Internal (1) & External (1) Total Atmospheric Pressure	kPA	30-110	1
Oxygen	3	Internal (1) & External (1) O_2 Concentration	%	0-100	1
CO_2	2	Internal (1) and External CO_2 Concentration	ppm	0-2000	100
Light (PAR)	2	Internal (1) and External (1) Photosynthetically Active Radiation (PAR)	μmol m-2 s-1	0-2000	2
Camera	1	Plant Health Imagery	RGB	1-255	>1k0x1k

c. Actuators

The MarsOASIS system has 24 electrically actuated components, including twelve pumps, a water heater, a water chiller, two fans, a UV filter, dehumidifier, oxygen concentrator, two solenoids, a linear actuator, a servo motor, and LED lights. All components are controlled by relay switches, with the exception of the driver controlled linear actuator, and the pulse width modulated, driver controlled lights and servo motor. The 12 pumps work together to accomplish recirculation, injection, and transfer of nutrient solutions as well as air intake, as described in the Nutrient and Fluids Management and Atmospheric Management sections above. Three recirculating pumps mix the nutrients to maintain a uniform composition throughout the solution. Three dosing pumps facilitate the injection of controlled quantities of nutrient and pH solutions in the mixing reservoir to maintain the desired fluid composition. Three transfer pumps carry the nutrient solution between mixing reservoir, leachate holding tank, and the growth bed. The humidifier pump pulls water through a tube that terminates in a misting nozzle to atomize the water added to the air. The air intake pump introduces the atmospheric air in the enclosed system. Finally the air bubbler pump introduces air into the mixing reservoir to maintain adequate dissolved oxygen levels. Figure 7 is a diagrammatic representation of all the pumps.

The water chiller and heater maintain water temperature in the mixing reservoir, and the UV filter provides pathogen control in the water supply. The O_2 concentrator, N_2 and CO_2 solenoid valves, dehumidifier, and fans maintain the atmospheric gas composition, pressure, and humidity. The linear actuator and servo motor are used to navigate the camera around the growth area. The linear actuator is mounted on the camera bracket to move the camera along the length of the bracket, as shown in Fig. 8. The bracket is actuated by a stepper-motor giving it a 180° swing.

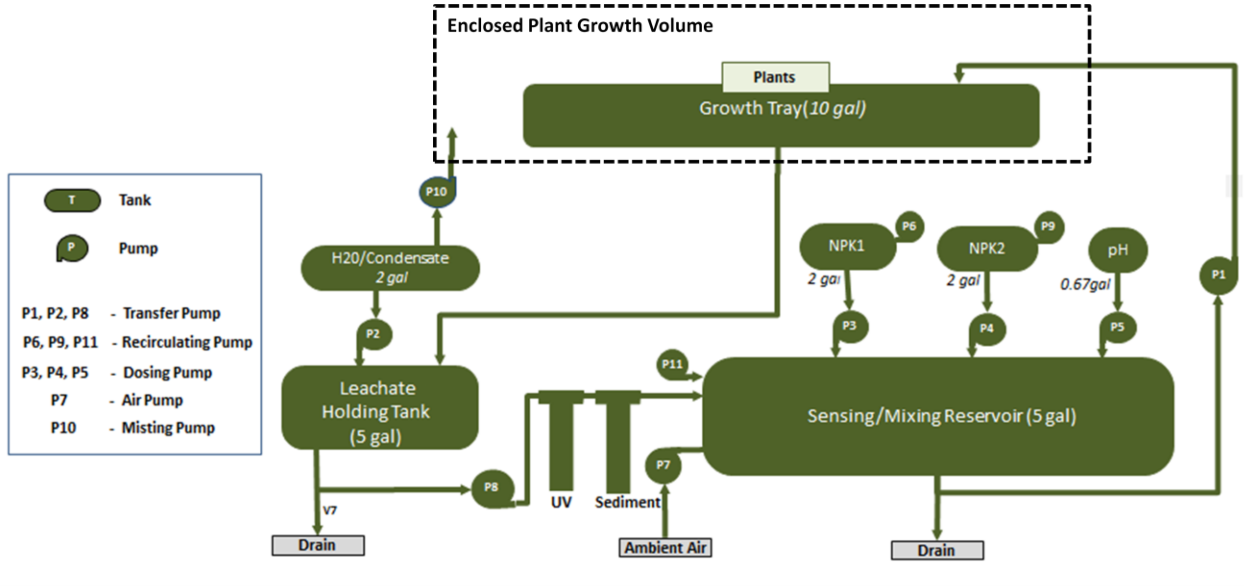

Figure 7. Diagrammatic representation of the complete pump system.

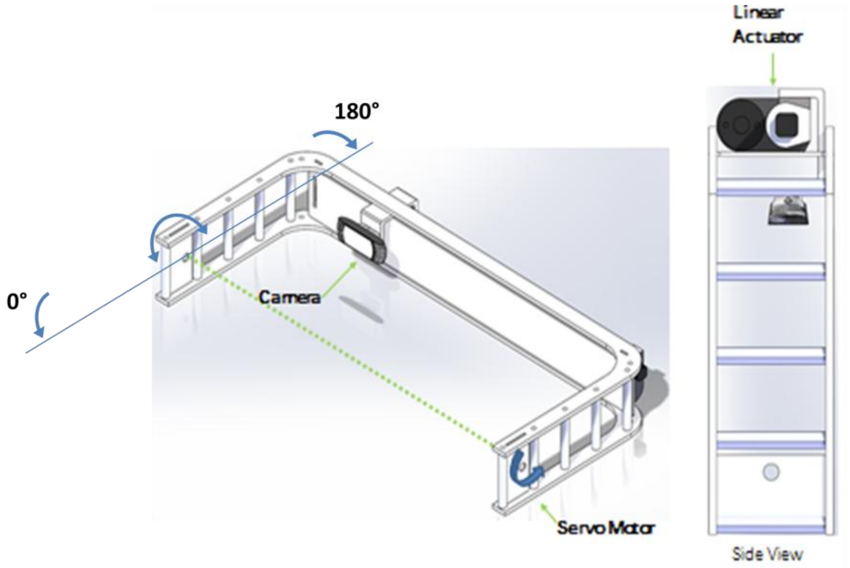

Figure 8. CAD model of moveable camera and LED bracket.

d. Autonomy and Teleoperation

The system is designed to allow continuous autonomous operation through mission lifetime. Sensed data is read into the microcontrollers through the sensor suite, processed and checked against the corresponding data range to determine whether the sensed parameter is within ideal conditions for the greenhouse. Examples of acceptable data values can be found in Table 3. Based on whether the sensor value drops above or below this range, the appropriate control action is initiated in the software. The control algorithm turns on or off the different actuators in the system to bring environmental conditions back to the range required for the plants. This is carried out through system feedback until the data is within the ideal ranges, as specified in Table 3.

Along with sensors for controlled atmospheric and nutrient content, the system camera is also programmed to autonomously capture images at the rate of one image per hour, to give a visual feedback about the progress of the plants. The images will be stitched to form a time-lapse video. These images as well as data from the sensors are accessed through the MarsOASIS website.

Table 3. Abridged Version of the Habitat Sensing Specifications Table (HSST)[15,16].

Category	Parameter	Units	Typical Min	Typical Max	Samples/hr
Internal Atmosphere	CO2 Partial Pressure	ppm	1000	2000	60
	Total Pressure	kPa	80	84	60
	Relative Humidity	%	50	70	360
	Temperature (Day)	°C	23	27	360
	Temperature (Night)	°C	18	22	60
Nutrient and Water Delivery	Soil/Medium Temperature	°C	15	20	60
	Water Temperature	°C	22	24	60
	Electrical Conductivity (EC)	μS-cm-1	1150	1250	60
	pH	--	5.5	6	60
Lighting Conditions	PAR	μmol m-2 s-1	200	250	60
	Light Cycle	hours on	18	24	N/A

While the system is capable of performing autonomously, authorized users are provided an override functionality that allows them to manipulate the microcontroller and directly affect the conditions in the system by changing the output of pumps, valves, and ideal ranges. This level of teleoperation also provides the user control of camera position along the bracket as well as the position of the camera bracket, thereby allowing a wide range of views of the growth bed.

VI. Conclusions and Future Work

The MarsOASIS team has been tasked with developing a deployable autonomous greenhouse for crop production on the Martian surface. Intended to be a precursor for crewed missions, the greenhouse would provide food for the astronauts arriving at a later time, further enabling a permanent human presence on Mars. MarsOASIS has developed a design concept for the Martian greenhouse and has prototyped a reduced-scope version in the spring of 2015. The conceptual design completed by the MarsOASIS team aims to understand the necessary constraints and capabilities of an autonomous greenhouse on the Martian surface including the subsystems needed to support it, the protection from the harsh environment, and innovative features that can make an autonomous greenhouse more feasible for future space missions.

It was found through the conceptual analysis and design that there are numerous challenges for a real Martian greenhouse mission including adapting to the environment, taking advantage of in situ resources to lower consumable needs, and making system alterations to perform in reduced gravity. As outlined above, the MarsOASIS team designed the conceptual system to survive the Martian environment through material selection, protection from dust storms with an actuated protective cover, and a substantial amount of insulation to regulate system temperature. To take advantage of that same environment's desirable aspects, the greenhouse utilizes in situ carbon dioxide to supplement the internal atmosphere needed for plant growth. Another in situ resource, natural sunlight, is utilized through the system's hybrid lighting system which supplements natural light with artificial LED light tailored to the plant's needs. These features allow the conceptual greenhouse to reduce consumable needs, making it more realistic for launch and landing on the Martian surface by lowering system mass and volume. To properly operate and control a greenhouse on the Martian surface, extensive autonomous control logic and teleoperation capability is required. The MarsOASIS team has developed the necessary control logic as well as an internet-based multiple-user GUI to remotely teleoperate the system in case of off-nominal conditions or for research purposes.

The prototype will demonstrate innovative technologies and solutions to many concerns such as the utilization of in situ atmosphere, a novel hybrid lighting system, and water recycling. The prototype will serve all necessary functions for crop growth, while also allowing plant science and crop production research in a controlled growth chamber. In future work, prototype performance will be characterized over multiple growth cycles to determine long-term reliability and efficiency. Also several prototype enhancements may be considered, such as support of reduced atmospheric pressure in the growth volume, support of multiple types of crops, support of multiple growth cycles, reduction of system volume, incorporation of additional or more accurate sensors, and software improvements for ease of control and data access. The MarsOASIS system prototype is intended to be used and enhanced by the University of Colorado Bioastronautics program to further develop the technology needed to enable sustained human presence in space.

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