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ARCHITECTURES FOR ACCOMMODATING LUNAR PLANT GROWTH DEMONSTRATIONS

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Abstract

Successful farming is essential for sustained lunar settlement, but as yet there is no established plan for showing it to be a real prospect. Robotic precursor experiments on Earth, in the ISS and on the Moon have been proposed and one small lunar example is underway as an adjunct to a Google Lunar X Prize entry, but much more work is needed. In this paper we discuss and advocate the design of habitat elements that can be created to begin our learning about ways to support plant growth as a part of integrated lunar living systems. These early, partial systems may be habitable for humans on Earth but not in ISS or on the Moon. Instead, they will be designed for human-supervised robotic operation to answer specific questions about plant accommodations through instrumented observation. Preliminary examples of this technique are the European Modular Cultivation System (EMCS) and the Optimizing Root Zone Substrates (ORZS) units existing aboard ISS. By growing the most important plants in real, controlled, observed lunar conditions we will be able to evaluate not only the plants themselves but also some of the architectural demands of accommodating them. Vertical farming is appearing in some cities, notably Singapore. On the Moon, if a silo can be drilled it can serve to house a vertical plant growth experiment, minimizing the top surface area to be shielded by regolith and enabling a compact plant support and observation system.

I. INTRODUCTION

The Global Exploration Roadmap (GER) from the International Space Exploration Coordination Group (ISECG) plans to have regular (every year) human missions on the Moon surface from 2018 (ISECG, 2013). The first missions would be one-month long and research and exploration performed during these first missions would enable longer stays on the surface. This will require considerable technology developments and testing in key domains. Among the ten top priority challenges identified by the NASA Space Technology Roadmaps and Priorities (Council, National Research, 2012), which are similar to the critical technology areas identified by the GER (ISECG, 2013) and ESA cross cutting technology roadmaps (ESA, 2013), the three with the highest priority are Radiation Mitigation for Human Spaceflight, Environmental Control and life Support Systems (ECLSS), and Lightweight and Multifunctional Materials and Structures.

ECLSS will very likely include plants since they contribute to revitalizing atmosphere, recycling water, and producing food. However very little is known about plant growth in partial gravity, as is the case on the Moon. Many experiments on plant growth were conducted in orbit in microgravity, since Oasis 1 on Salyut 1 in the seventies (Porterfeld, Neichitailo, A.L., & Musgrave, 2003) until now with Lada (NASA, 2005) and Veggie aboard the International Space Station (NASA, 2014). The European Modular Cultivation System (EMCS) on the ISS since 2006 enables to experiment with plant germination and early growth in partial gravity, ranging from 0.001 g to 2.0 g (ESA, 2009). But currently no facility provides the opportunity to grow plants on a whole life-cycle, from seed-to-seed, in partial gravity, although this will be a critical initial step in establishing the first long-duration human missions on the Moon.

As underlined in NASA Space Technology Roadmaps and Priorities (Council, National Research, 2012), before hosting the first human settlement, the Moon could be used for experiments and testing in partial gravity environment to prepare for further exploration of the solar system, e.g. Mars. The lunar surface could be a testbed for growing plants in Martian gravity, using a big-scale centrifuge.

Many other aspects related to plant growth need to be investigated such as automated greenhouses, the structures needed to grow plants in the harsh lunar environment, illumination of plants, use of regolith as plant media, or use of plants as ISRU products. Some are discussed in this paper. Finally we describe a plan to allow for inexpensive experiments on Earth and on the ISS that can be done by students, followed by small robotic missions on the Moon.

II. REVIEW OF CANDIDATE CROPS

Candidate crops for future distant space missions have been extensively reviewed (Mitchell, 1994). Main criteria for crop selection include, among others, energy content, nutritional composition, palatability, serving size and frequency, processing requirements, use flexibility, storage stability, toxicity, human use experience, proportion of edible biomass, yield of edible biomass, continuous vs determinate harvestability, growth habit and morphology, environmental stress tolerance, photoperiodic and temperature requirements, carbon dioxide and light intensity response, and pollination and propagation (Hoff, Howe, & Mitchell, 1982; Mitchell, 1994). However little is known about dietary requirements of humans in partial gravity, which might be different from what is required on Earth (Mitchell, 1994).

The first plants grown on the Moon for astronauts' feeding will very likely be fast-growing salad crops (lettuce, cherry tomato, radish, and sprouts) and herbs (chive, mint, parsley) (Mitchell, 1994) to supplement astronauts' diet. Their main purpose will be to bring vitamins, minerals, and fibers to the astronauts, as well as variety in their food, but also freshness and different textures, important factors for psychological well-being (Mitchell, 1994). Herbs will enable to bring more flavors to the food, important to prevent the crew from being tired of what they eat.

When missions on the Moon are longer and move toward settlements, it will become necessary to produce food on site and thus to select crops that can fulfill humans' dietary requirements. Astronauts' diet will likely become vegetarian, based on legumes and cereals (Mitchell, 1994). Oily (e.g. soybean) and non-oily legumes (such as beans or cowpeas) will provide the crew with proteins and fats. To achieve amino acid complementarity of cereals and legumes, wheat and/or rice will be grown as well (Mitchell, 1994). They will also provide complex carbohydrates. Potato and sweet potato are also in the list of crop candidates because they would provide complex carbohydrates (Mitchell, 1994). More vegetables such as broccoli or spinach will likely be grown as well, to create variety in the dishes (Mitchell, 1994).

III. EXPERIMENTATION/SCIENCE NEEDED AND PLANNED OR ON-GOING TESTS

III.I Automated greenhouse modules

Although gardening is a very calming activity, providing psychological relief to astronauts on long-duration space missions (Haeuplik-Meusburger, Paterson, Schubert, & Zabel, 2014), when it comes to feeding astronauts with plants, the greenhouse module will be enormous (from 500 to 1000 m^2 of growing area if the diet relies 100% on plants grown in it (Eriksson, Doule, & Poulet, 2014)), also (Ciardullo, 2014) and will thus require many full-time crew members working on it. This is not desired on a space mission, where astronauts have to focus on the mission itself, as well as on the multiple science experiments they are assigned to do. For this reason, the greenhouse module, designed to sustain the astronauts on a long-duration mission, should be mostly automated. This goes for the following aspects: sowing, harvesting, watering, illumination, environmental control, and plant health checks.

Many aspects of controlled-environment growth on Earth, like illumination or watering, are automated. This is particularly true in big facilities, where hand-watering would take too much time. In addition, an automated watering system ensures that each watering session delivers the same amount of water to the plant.

Experiments at the research center of Wageningen University (The Netherlands) are underway for automated seeding and harvesting of plants, as well as plant health monitoring (Jansen, Hofstee, Bouwmeester, & Van Henten, 2010; Pekkeriet; New AC International, 2011).

A partially automated greenhouse module hosted in a 40-foot container is planned to be installed at the German Neumayer Research Station in Antarctica in 2015. This project, conducted in the frame of the Evolution & Design of Environmentally-closed Nutrition sources (EDEN) group within the German Aerospace Center (DLR), aims at testing technology and procedures in relevant operational scenarios to prepare for future planetary long-duration missions (Bamsey, Zabel, Zeidler, L., & Schubert, 2014). The container will be operated during a whole winter season (9 months from March to November) and sustain the crew with fresh vegetables.

III.II Materials and structures of a lunar greenhouse in lunar environment

The early greenhouse facilities are likely to be growth chambers included in the lunar habitat, only supplementing the astronauts' diet with salad crops (e.g. lettuce and radishes) and herbs, as explained in section III. But when missions are longer and the astronauts' diet mainly relies on plants, larger greenhouse modules will be needed. These will be modules independent from the habitat and linked to it by hatches. Thus their external structure will need to be resistant to the harsh lunar environment, i.e. provide adequate radiation and meteoroid protection, thermal insulation able to cope with extreme temperature changes, and be strong enough to resist changes in pressure between the outside (close to vacuum) and the inside (close to one atmosphere).

To fulfill all these requirements, it is very likely that the greenhouse module will be buried under layers of regolith or will have water walls (Doule, Detsis, & Ebrahimi, 2011; Sinn & Doule, 2012). Some studies also suggested storing mission wastes in the walls to provide protection against the environment (Aron & Grossman, 2013). All these options need to be tested on Earth prior to developing them on the Moon and this can be done in facilities providing space-like conditions. The test center at the European Space Research and Technology Center (ESTEC) in the Netherlands is equipped with the Large Space Simulator (LSS) which can recreate space-like conditions in Earth orbit: vacuum level of one-millionth of a millibar, sudden temperature changes, and solar energy intensity of one solar constant (1380 W/m^2) (ESA, 2010). These conditions are the same on the Moon and so the materials intended to be used for the greenhouse module could be tested in such a facility.

III.III Plant growth in partial gravity

Extensive research on plant growth has been conducted on the ISS, from germination and early growth to whole-life cycle and seed-to-seed experiments. Results showed that plants grow normally in microgravity but an experiment conducted in 1997 in the Svet greenhouse showed that seeds decreased in viability from one generation to another (Foale, 1999). On the other hand in April 2014, a cherry tree from a cherry pit that travelled in space in 2009, bloomed four years earlier than expected (GRIFFITHS, 2014) and an experiment with tomato seeds, which spent 6 years on the ISS showed that they germinated faster (Foale, 1999).

To date no plant experiment was conducted on a whole life-cycle in partial gravity, only on germination and early growth in the EMCS centrifuge on the ISS. Thus crop yield and plant development still remain unknown in partial gravity.

Plans for a larger centrifuge on the ISS were made several years ago and the Centrifuge Accommodation Module (CAM) was already partially built when the program got cancelled (JAXA, 2003). No replacement was envisioned by any space agencies yet but a plan to temporary accommodate a large-scale centrifuge on the ISS was elaborated by James Burke et al. at the IAA Space Exploration Conference (Burke, Coderre, & Jaime Albalat, 2014).

NASA Ames Research Center is planning to put a small-scale growth chamber in one of the landers of the Google Lunar X-Prize in late 2015 to study germination of plants in lunar gravity and radiation environment. The experiment is planned to last 5 to 10 days. Follow-up of this experiment includes 14-day, 60-day and 180-day experiments to test sprouting, reproduction functions, and genetic modifications in the lunar environment (NASA, 2013).

III.IV Plants as part of a bioregenerative Life Support System

Many studies have included higher plants and micro-organisms to create a life-support system for future space missions. The European Micro-Ecological Life Support System Alternative (MELiSSA) project has a ground demonstration unit at the University of Barcelona and is based on five compartments – three microbial-based, one with higher plants and algae and the crew compartment (Lasseur, et al., 2010). Wastes of the crew are degraded into single elements that are then used to feed plants and algae.

A study to design a greenhouse module on the Moon within the MELiSSA loop is currently under work in the EDEN group at the German Aerospace Center (Poulet, et al., 2013). The outcome will give a comprehensive assessment of what it takes in terms of energy and power, mass, volume, and technology to sustain a crew of six on the Moon, exclusively on a plant diet.

More research is needed in this area to study how micro-organisms and plants react in lunar conditions and extensive tests are needed to validate the closed-loop in lunar gravity.

III.V Plant illumination

Plants on the Moon can be grown under electrical light, under natural sunlight or under a combination of both (hybrid lighting system).

The inconvenient aspect of electrical lighting is that it is very costly in terms of energy; however, it enables full control of light composition, intensity, and photoperiod. Sunlight virtually is unlimited and does not require nuclear reactors or hectares of solar panels to work.

Greenhouse modules being likely to be covered under layers of radiation protection, sunlight will have to be transmitted via fiber optics, increasing the system's complexity. Another inconvenience of a lighting system only relying on sunlight is that, depending on the location of the greenhouse module on the Moon, nights can be up to 14 Earth days long. If it is decided to solely go with a natural lighting system, then experimentation on Earth should be performed on the growth of plants exposed to a certain number of days of continuous light followed by a certain number of days of continuous darkness.

Hybrid lighting systems seem to be most adapted to lunar lighting conditions since plant lighting can be assured by the electrical lighting system when sunlight is unavailable. Experiments must be performed on Earth to test plant reactions to alternate light quality – from all natural or natural plus electrical to all electrical – since to date electrical lighting is unable to accurately reproduce the full sun spectrum.

III. VI Use of lunar regolith

Microgravity experiments to study water retention in both simulated and real lunar regolith have been performed, in parabolic flights (Heinse, Jonesa, Steinbergb, Tullerc, & Or, 2007) but also in the Optimization of Root Zone Substrates (ORZS) facility in the ISS (NASA, 2014). However these experiments were not performed in lunar gravity yet. These tests still need to be done.

Another phenomenon, whose understanding is critical for plant growth in lunar regolith in lunar gravity, is the clay transition of lunar simulant, observed on Earth, after several months of plant growth. This could be easily tested on the ISS centrifuge with terrestrial controls (Burke, Coderre, & Jaime Albalat, 2014).

III. VII Use of plants as ISRU products

Instead of being discarded, inedible parts of plants could be used to manufacture objects needed in a lunar settlement. For example, structural materials could be made of lunar regolith mixed with dried inedible parts of plants, imitating clay and straw, for construction purposes. These unused parts of plants could be dried and reduced to powder for later use in 3D printers to manufacture useful components. Pulp molding technology could also be used with inedible parts of plants and then recycled and reused, as suggested in the NASA Space Technology Roadmaps and Priorities (Council, National Research, 2012). It is also advised to investigate the incorporation of many wasted materials (not only inedible parts of plants but also packaging for example) into new products.

Waste biomass from crops grown for food could also be used to manufacture flexible textile or rigid covers to be placed on the regolith surfaces. This would be less energy-intensive than deriving them from the regolith itself (Council, National Research, 2012).

IV. PLAN FOR LUNAR PLANT GROWTH DEMONSTRATIONS

IV.I Inexpensive experiments on Earth

Many small-budget experiments can be performed here on Earth to test technologies prior to space adaptation for a mission on the Moon.

Automation of greenhouses and illumination systems can be demonstrated and tested on Earth in the first place, using existing growth chambers in universities for example. This is already done in many places, but a unified effort toward specific Moon environmental conditions would help progress to grow plants on the Moon.

ISRU products from plants can be manufactured here on Earth and tested before using them for a mission on the Moon. This effort would focus first on defining what kind of objects will be needed during a lunar mission and what can realistically be made with inedible parts of plants. Then design and manufacturing of these objects can be easily tested and on low-budget. Students could be involved through thesis or school projects work on this.

IV.II Experiments on the ISS

Since small centrifuges are already on the ISS, they could be used to study germination and early growth in lunar regolith in the partial gravity of the Moon. The NASA Flight Opportunity would be a good way to start.

As a further step, a bigger centrifuge could be anchored to the ISS temporarily to test whole-life plant cycle grown in lunar regolith in lunar gravity.

IV.III Small robotic demonstrations on the Moon

Small-scale automated greenhouses can be landed on the lunar surface for short periods of time with fast growing salad crops initially. This is what the experiment planned by NASA Ames Research Center with a lander of the Google Lunar X-Prize is scheduled to do in 2015.

But this should not stop at this small-scale experiment. Many missions are under development to go to the lunar surface before 2020: Chang'e 4 (China) in 2015, Luna-Glob 1 (Russia) in 2016, Chandrayaan-2 (India) in 2017, Chang'e 5 (China) in 2017, Luna-Glob 2 (Russia) in 2018, and ILN Node 1 (USA) in 2018. Additionally, Japan is planning a robotic probe SELENE 2 for 2017 and Europe a Lunar Lander in 2018. All these missions could bring small greenhouse payloads and test early plant growth in real lunar environment. This would give great insight on phenomena such as evapotranspiration transfer, migration of water in the plant, and photosynthesis.

Human missions to the Moon are planned as early as 2020 by the Indian Space Program and Japan Aerospace Exploration Agency (JAXA). The European Aurora program as well as the Chinese space program plan to land humans on the Moon. These missions could bring greenhouse modules or plant chambers with them and experiment on whole-plant life cycle in lunar gravity and lunar radiation environment, as well as contributing to sustaining astronauts' diet.

V. PREPARING FOR THE FARTHER FUTURE

With the previous discussion as a basis, and assuming a small pioneering settlement successfully implanted, let us now turn to considering work that could begin now to lay the foundations for lunar architectures in a later stage when a full-scale society is established on the Moon.

In the more distant future it is fair to imagine great advances in technology and management, but some fundamental constraints will remain: It will still be essential to limit the transport of materials between Earth and Moon and to use free and instant information transfer to support a two-world civilization. Plant growth should proceed toward large-scale, long-duration agriculture and forestry with the reliable and sustained supply of plant products for uses beyond just supporting the life and productivity of settlers. Examples would be cotton for textiles, bamboo for structures and furniture and small fruit trees, flowers and butterflies for enjoyment.

To build confidence in these broader plant uses, precursor demonstrations on Earth, in orbit and on the Moon will be required. A particular focus of this paper is on lunar architectures enabling such demonstrations in real lunar conditions.

VI. LUNAR HAZARDS AND WAYS TO COPE WITH THEM

On 17 March 2014 an object hit the Moon leaving an 18-meter-wide crater. The impact flash was observed from Earth (NASA, 2014). This was only the largest of at least four such events happening during the operation of the Lunar Reconnaissance Orbiter. Such an impact would be a severe threat to the roof of an underground habitat. One way to limit the risk of damage is to limit the area of exposed roof, and another is to enhance the thickness and strength of the roof.

It might be thought that the impact hazard is a reason to choose a lava tube as a habitat site. Tubes with skylights, holes where the roof has collapsed, are known on both the Moon and Mars. Here, for two reasons, we do not consider this option: First, not enough is known about actual tube roof strength, and second, no tubes are observed in the lunar polar regions that are now preferred as settlement locations.

Limiting roof area implies limiting the architectural choices for at least the entryway into the subsurface enclosure. When considering advance precursor installations supporting plant growth demonstrations it is then natural to examine the prospect of vertical farming. This is increasingly practiced on Earth in settings where agricultural land area is at a premium, notably Singapore (Skygreens, 2014).

VII. CONSEQUENCES OF VERTICAL FARMING

Water and nutrient supply, waste control, atmosphere maintenance and illumination are all solved problems in vertical greenhouses on Earth. In a subsurface lunar habitat, providing these functions presents new architectural challenges.

We have to assume that water extraction from natural sources will have become a standard technique and water storage established in subsurface reservoirs, as required in any event for crew life support. Beginning with small shipments from Earth, nutrient supply can be bootstrapped as greenhouse content expands. Illumination will probably be hybrid, as discussed earlier above. With the habitat sited in a polar region, nearly-perpetual sunlight can be piped in from a Sun-tracking tower on the surface and distributed as needed in the greenhouse. Demonstrating reliable achievement of these functions will be an important goal of precursor greenhouse architecture.

Harvesting will, at least at first, be mainly robotic. Present-day robotics can do this rather clumsily but developing improved techniques is an obvious architectural objective and demonstrations on Earth and in orbit should be part of any program plan.

VIII. EXPANSION TO SETTLEMENT

A narrow conduit to the surface, with vertical farming, is a prudent first architectural step, but ultimately a much larger underground chamber area will be needed to support a true permanent settlement, not only for human habitats, work spaces and public facilities but also for crop land.

Excavating such a mammoth chamber, especially in a polar region where the regolith may be saturated with ices, is a problem whose magnitude is now unknown. Some knowledge may be gained via robotic missions seeking to evaluate the potential of the ice resource, but if we are serious about establishing a two-world civilization we must ultimately face the question of creating very capacious underground spaces. Given the inevitably long lead time for this process, it is now not too early for architects and engineers to begin contemplating and discussing lines of attack including precursor demonstrations on the Moon. Plant growth verification experiments should be a part of any such precursor architectures.

When contemplating permanent habitation we should be aware that settlers will ultimately want animal protein and other animal foods in their diet. Human nutrition needs in microgravity space flight are well documented (Lane and Schoeller, Eds., 1999) but nutrition in real, long-term lunar conditions is still a topic for demonstration.

With cattle and sheep ranching surely impractical – and in any event very inefficient – starting with insects, a long-established food in the Orient, may be a good solution (Hodson, 2014), but immediately we need to ask what is to be fed to the insects. If they are herbivorous, then insect food plants must be added to the research list. Later, small edible creatures such as ducks and miniature pigs (also common in the Orient) may be added, with a concomitant need for appropriate plant research. Dairy products are a special challenge because cows are so big. Perhaps continual deliveries of milk concentrates from Earth will be needed. If so, lunar architectures must accommodate them.

With this planning underway it should be possible even in the near future to begin significant progress toward the far-future objective of human living with sustained and reliable agriculture and forestry on the Moon.

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