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White Paper

The Space Agriculture Endeavour

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This white paper was initiated during the 6th International AgroSpace Workshop, held in Sperlonga, Italy from May 22nd – 23rd, 2014 and was subsequently refined in the months following. We are members of international research centers, academia and the space industry, who cooperate to design, develop and test greenhouse-based Bio-regenerative Life Support Systems (BLSS). We reflect a multidisciplinary group of international experts representing aerospace engineering, plant science, horticulture, microbiology, food science, medicine, architecture and psychology. The purpose of this position paper is to layout the advantages and challenges of utilizing higher plants as an essential part of BLSS for long-duration human space missions. The white paper's objective is to convince decision-makers within government and space agencies to invest in this development pathway and to pave the way to a fruitful future of space exploration and terrestrial growth.

Sustainable Presence in Space and on Earth

Sustained human presence in space requires the development of new technologies to maintain environment control, to provide water, oxygen, food and to keep astronauts healthy and psychologically fit. Furthermore, the logistics of mission resupply limits human exploration in space. BLSS in conjunction with in-situ resources will initially reduce and ultimately eliminate consumables from the logistics chain. Minimizing this need for resupply while ensuring human safety will allow astronauts to travel further and stay longer in space than ever before. While physical/chemical life support systems would form the back-bone as a fallback strategy, the BLSS would expand to eventually become the prime system ensuring sustainable life support for long-duration missions.

Many international advisory groups are highlighting the necessity to further develop such regenerative systems (NASA, 2010, Technology Frontiers: Breakthrough Capabilities for Space Exploration'; European Science Foundation, 2012, THESEUS Roadmap; ISECG, 2013, Global Exploration Roadmap).

Unrivaled Features of Plants

The cultivation of higher plants can contribute to all major aspects within BLSS and represents an all-in-one-approach, not accomplished by any single physical/chemical system.

The most apparent advantage is the provision of food. Fresh food provides essential vitamins, minerals and other useful macromolecules such as useful bioactive compounds to support crew health, and function this way as countermeasures for the stresses associated with deep space exploration.

Considering the symbiotic relationship between humans (carbon dioxide emitters) and plants (carbon dioxide absorbers), plant growth modules will also provide valuable oxygen to the crew. NASA studies have demonstrated that the oxygen needs of a single crew member could be met by approx. 10-20 m^2 of plant area.

Through the exploitation of plant evapotranspiration, the deployment of plants can furthermore contribute to wastewater recycling. Recent research from the Lunar Greenhouse test stand at CEAC (University of Arizona) has shown that 12 m^2 of plant area could generate up to 21 L of potable water per day. Research at the Chinese's Lunar Palace 1 test stand at Beihang University showed that 23 m^2 of plant area can generate up to 60 % of dietary needs for one person.

Astronaut physical and psychological well-being is vital, especially during long duration missions with constant isolation in a highly-integrated machinery environment, including the dependency on these machines. The visual appearances of plants ('nature') as well as activities with them ('gardening') and associated design and architectural solutions can greatly enhance the psychological well-being of the crew.

From a long-term perspective, bio-plastic, latex, or other high value compounds that can be generated from plants, will also help reduce consumables and increase mission autonomy. Transforming bio-plastics into granulates and using them with the latest 3D printing techniques, opens a wide variety of in-situ production capabilities.

Accomplishments and Challenges

Significant investments in unique research infrastructure like Controlled Environment Agriculture (CEA) laboratories, plant test stands, and analogue test sites were completed in recent years to investigate essential aspects of (semi) closed-loop plant cultivation and to develop the required plant cultivation technologies.

Through the implementation of CEA technologies that carefully control and optimize the provision of nutrients (e.g., H_2O, pH, electrical conductivity, as well as soilless cultivation), environmental conditions (e.g., temperature, relative humidity, concentration of CO_2 & O_2), and light, including spectral composition (e.g., red, blue, UV), it is now possible to achieve higher yields and shorter growth cycles. Through CEA, even the exact control of food quality is possible (e.g., phenotype, taste, enrichment of useful substances => functional food).

Nevertheless, challenges exist in developing cultivation systems. Several key technologies necessary for space-based plant production are not yet space-qualified or remain in early stages of development. In order to achieve higher Technology Readiness Levels (TRL), higher contributions and budget allocations in respective projects and programs need to be assigned.

Technology gaps include: self-regulating multi-nutrient delivery systems, low mass and actively-cooled LED lighting systems, efficient approaches for capturing and delivering solar light, low-energy water recovery systems, semi-automated planting and harvest systems to minimize crew time, and crops tailored specifically for the constraints of space (e.g., dwarf growth, high harvest index, high productivity). Furthermore, post-harvest procedures including food safety assays need to be developed and tested.

Terrestrial Benefits

The production of plants with resource-efficient and space-based regenerative principles has great impact on commercial agriculture and contributes to many different socially important challenges that the world faces today (e.g., eco-intensification of production systems, sustainable management of natural resources, contributions to a sustainable food chain and a global food security system).

Climate change is affecting food production through desertification, transforming once fertile lands into inhospitable deserts. Modified greenhouse modules, located in desert regions, can provide an opportunity to utilize these areas for agriculture. Greenhouses optimized with closed-loop habitat technology excel in this purpose due to their low water requirements and waste outputs compared to traditional agriculture. The ability to grow crops throughout the whole year, and minimize crop losses due to drought, insects) and diseases, make these greenhouse modules a potential solution for agriculture in other hostile climates (e.g. polar areas) as well as in remote location (offshore facilities, remote villages, islands, and isolated work sites). Furthermore, critical areas of need include ensuring a safe food supply under emergency conditions following natural disasters (hurricanes, earthquakes, floods), humanitarian crises (famine, refugee camps), and political unrest (military and humanitarian support roles).

One of the recent mega-trends in society is urban agriculture, where vertical farming is a proposed cultivation technique involving large-scale agriculture in urban high-rises or "farmscrapers". These buildings would be able to produce fruits, vegetables and other consumables like pharmaceutical plants (e.g. molecular farming) throughout the entire year independent of season, climate, region and sunlight, offering high yields and nutritional values, while using 98% less water than traditional open field agriculture. This technology will not only save water, fertilizer, and space, but reduces or eliminates discharge into the environment as well. Most importantly, it will be a key technology to secure future food supply of cities while decreasing their ecological footprints.

Public Engagement

The fascination of space agriculture is something that the spectrum from young students to grandparents can relate. Plants are something that nearly all people can connect with, whether it is from having a direct "green thumb" experience or simply as a consumer of fruits and vegetables, the importance is obvious. Combining plant growth with space exploration further adds to this fascination and this has been used by a number of countries and leaders in educational curriculum development as a tool to motivate learning across any number of the associated subjects (e.g., mathematics, biology, physics, logistics, sustainability). This has been explicitly demonstrated through highly successful space learning programs such as Tomatosphere, which in Canada and the US alone has reached over 16000 classrooms. We understand the importance and the benefits for the continuation and further enhancement of programs such as the Canadian Space Agency and University of Guelph Tomatosphere project and other notables such as DLR_School_Lab, University of Arizona Lunar Greenhouse Project, the Beihang University Lunar Palace 1 outreach program, and the NASA led International Space Apps Challenge.

Conclusion

Bio-regenerative air revitalization, water recycling, waste management and the sustainable production of nutritious food for human survival in space is a challenge that needs to be overcome, not only for space, but also for terrestrial applications.

This research direction can lead to resource-efficient, sustainable living and strengthen the global food, energy and waste recycling industries. The imperatives for this research endeavor are critical and challenging, and the requirement to adapt the CEA technologies for the space sector adds even further challenge. Nevertheless, by investing in this research, new cultivation approaches in producing food and other useful bio-products can be achieved in a resource-efficient manner.

The overall goal is the adaptation, integration and demonstration of higher plant cultivation technologies and operation procedures for safe food production on-board present and future space vehicles (starting with ISS) as well as in future, long-term planetary outposts.

Out of necessity, these actions have to be initially performed on the ground, both in, laboratory environments as well as in extreme environment test beds, such as highly-isolated Antarctic research stations. That is why we believe that much of the essential background technology exists to move forward towards exploration, and we are committed to seeing large-scale, integrated systems evaluated under mission relevant conditions with an analogue mission greenhouse (e.g. Antarctica) in 2017, a full-rack plant growth payload on ISS by 2021, and large-scale payload on either ISS or the lunar surface by 2025. We are hopeful that funding mechanisms in the space agriculture domain will permit these activities and their associated terrestrial benefits to be realized.

Signatories on next page

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