Bio-regenerative Life Support Systems at DLR

Roadmap in the context of international collaboration 2020 to 2030

DLR

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Motivation

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. Bio-regenerative Life Support Systems (BLSS) in conjunction with space resource utilization 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.

The cultivation of higher plants can contribute to all major life support functions 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, other useful macromolecules and bioactive compounds supporting crew health and, thereby, serves as a countermeasure for the stresses associated with deep space exploration.

Figure 1: Left: C.R.O.P.® - Laboratory at DLR Cologne (Institute of Aerospace Medicine); Right: EDEN ISS greenhouse system during its initial deployment in Antarctica in 2018 (Institute of Space Systems, Bremen).

Considering the symbiotic relationship between humans and plants, greenhouse modules will contribute to air revitalization and nutrient recovery. Plant photosynthetic activity consumes carbon dioxide, exhaled by the crew, and provides valuable oxygen. Nutrients contained in human wastes are suitable for plant growth after microbial conversion. Furthermore, through the exploitation of plant evapotranspiration, plant cultivation, based on treated wastewater, can contribute to water recycling. Astronaut physical and psychological well-being is vital, especially during long duration missions with constant isolation in a highly-integrated technical environment, including the dependency on machines. The presence 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.

Over the last decade, the German Aerospace Center (DLR) has been actively developing key technologies, which can be part of a comprehensive BLSS. The DLR Institute of Space Systems and the Institute of Aerospace Medicine have joined forces in order to design a life support module for deployment within a planetary outpost infrastructure for the Moon and Mars. The Institute of Aerospace Medicine has developed the C.R.O.P.®-biofilter technology, which can process urine into nutrients for plant cultivation (see Figure 1, left). Plant cultivation experiments comparing the performance of crops, such as Micro-Tina super dwarf tomatoes, grown on a conventional nutrient solution with those grown on a C.R.O.P.®-enhanced nutrient solution are ongoing. At the same time, the technology has been adapted for use on the Eu:CROPIS satellite which aimed to test the performance of the process under different gravity levels.

The EDEN research group of the Institute of Space Systems has developed and tested Controlled Environment Agriculture systems to allow successful plant cultivation. Most recently, the EDEN research group led an international consortium in the design and construction of a (semi-) closed-loop greenhouse system for subsequent testing in a space-analogue environment in the Antarctic. The greenhouse, known as EDEN ISS (shown in Figure 1, right), has been in operation near the German Neumayer-Station III in Antarctica since the beginning of 2018.

As a result of the multiple projects carried out by the two research groups during the past decade, the systems being developed have reached a level of technological maturity, which will enable both groups to develop a joint BLSS module to further advance the state-of-the-art.

Bio-regenerative Life Support System - Ground Demonstrator

The envisioned ground demonstrator represents a full-scale, space-rated greenhouse system that is able to provide fresh vegetables and fruits (as supplement food source in combination with pre-packed meals) for a crew size of six astronauts. A food provision rate of 20-40% is envisioned for this type of design, accompanied by other benefits such as atmosphere revitalization, and water recycling capability.

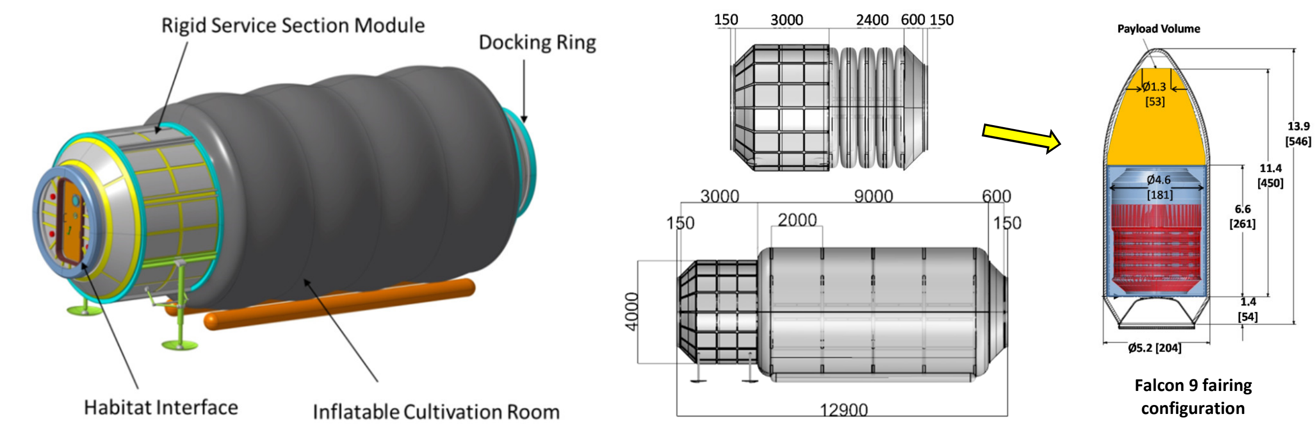

Figure 2: Left: Deployed Bio-regenerative Life Support System (BLSS) module; Middle: Stowed BLSS module configuration and dimensions [in cm] (top), deployed configuration and dimensions [in cm] (bottom); Right: Fairing dimensions (in meters and inches in brackets of Falcon 9 (smallest configuration) with the greenhouse module in the transfer configuration including the cover protecting it against debris and radiation during transfer (blue, ca. 0.30 m thick). Remaining volume (orange section) offers space for the docking vehicle).

A preliminary structure has been designed utilizing a hybrid cylindrical rigid/ deployable approach. The primary structure consists of an inflatable membrane shell with a rigid section on both ends (Figure 2). The structure expands in both the longitudinal and radial direction upon deployment and is supported by a number of rigid flanges, which can be deployed telescopically. The stowed configuration is designed to fit in an envelope with a diameter of 4 m and a length of 6.3 m, and upon deployment, the total length will increase to 12 m and the membrane shell will expand to a diameter of 5 m. The design parameters of the service section module were chosen as an analogue to the rigid pressurized modules currently used for the International Space Station and various cargo vehicles.

The membrane shell is connected on both ends to the rigid sections (the service section module and a rigid interface/ docking ring), but also connects to internal rigid frames, spaced evenly along the length of the deployable section. These rigid frames are connected by hinged spacers and longerons which allow for packaging and deployment in the longitudinal direction.
To achieve the packaging needed for fitting the launcher fairing, both a longitudinal and radial expansion of the membrane shell is intended. Upon surface deployment, the radial expansion offers accommodation of the plant cultivation area, by allowing for three plant cultivation racks (one on each side with one central rack).
An initial evaluation of the subsystem volumes, masses, and their accommodation was carried out to determine the feasibility of fitting all components within the stowed BLSS module for a single launch scenario. With a total mass of 15800 kg, including a 20% safety margin to account for the uncertainties in the design, the total mass is below the maximum payload mass of the Falcon 9 launch system (22800 kg to LEO). Additionally, the assumptions regarding the docking vehicle were investigated and incorporated into the design considerations. For the overall mission scenario, a given interplanetary transport infrastructure, incl. landing device and planetary surface mobility is assumed.
The preliminary internal design of the ground demonstrator will provide approx. 30 m² of cultivation area, of which 60% is assigned to short crops (e.g. lettuce, herbs) and the remainder is utilized for tall crops such as tomatoes and cucumbers. Based on performance values and lessons learned from the Antarctic EDEN ISS operations phase, the envisioned space food production system will provide up to 90 kg of fresh food per month for a crew of 6 astronauts (0.5 kg per astronaut per day) and could contribute to a significant percentage of the crew's caloric intake.

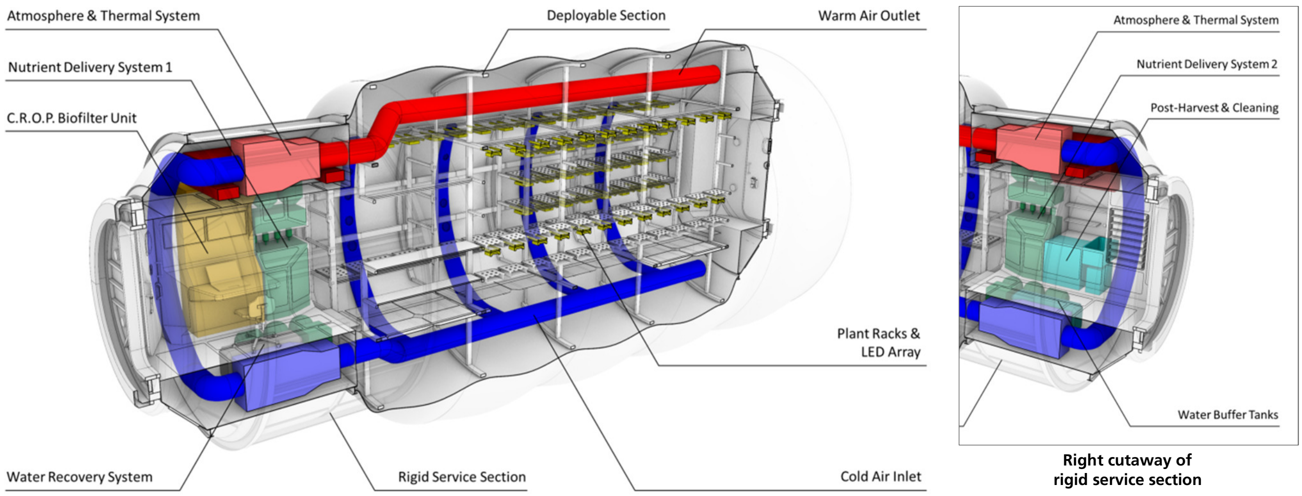

Figure 3: Left and right cutaway of the DLR BLSS test demonstrator.

The ground demonstrator offers sufficient space within its rigid service section to accommodate further life support systems. Envisioned is the integration of a biological urine nitrification unit, based on the C.R.O.P.®-biofilter technology, which will mainly be responsible for transforming the astronauts' urine into adequate liquid fertilizer. This fertilizer solution will then be used within the cultivation area as the basis for the irrigation solution. This way, the system evolves towards a full life-support segment and an additional loop (here: urine loop) can be closed within the habitat infrastructures.
Although intended as a ground-based prototype system, the BLSS module design shall strictly follow space requirements, including the use of space-qualified subsystems, components, and materials, as well as the implementation of accommodation- and redundancy strategies for adequate system performance tests.

Research- and Development Pathways until 2025

The roadmap (see Figure 4) depicts the research activities of the Institute of Space Systems and the Institute of Aerospace Medicine for the next decade (2020 to 2030) for both space and terrestrial applications.

The roadmap can be split into two distinct periods. The first years of the roadmap culminate in 2025 with the construction of the BLSS demonstrator. To enable the successful construction of this space-rated demonstrator module, the roadmap defines a number of development pathways which merge into the demonstrator hardware deployment.

The analogue testing pathway foresees the use of the existing EDEN ISS greenhouse as a space-analogue research platform in the Antarctic to test novel components and systems in a relevant environment. Lessons learned from its operations will be used to mature the design of the systems, and hence of the BLSS demonstrator. Furthermore, system updates will be implemented in order to improve reliability and reduce energy consumption. Finally, efforts to reduce crew time demand of the Antarctic system will focus on integrating a robotic arm, along with artificial intelligence, to allow a number of additional tasks to be automated.

The space food production pathway covers all activities which will be carried out in the EDEN laboratory. This laboratory is currently being upgraded to enable the EDEN group to carry out development and testing of Controlled Environment Agriculture (CEA) technologies. The nutrient delivery system is one particular focal area, with the group aiming to develop a more reliable aeroponic irrigation system. Furthermore, an energy-efficient and more robust atmosphere management system will be developed (e.g. anti-microbial coatings).

Similarly, the biological waste recycling pathway covers the laboratory work carried out by the Institute of Aerospace Medicine, with the main focus for the next years being the design and test of a sewage and solids processing system. The combination of different waste streams (urine/blackwater and inedible plant biomass) aims at creating a liquid fertilizer solution, which satisfies the nutritional requirements of the plants to a large extent, thus reducing the need of mineral fertilizer supply. C.R.O.P.®-systems are always designed according to the principles of maximum performance stability and simplicity of structure to minimize maintenance effort. Therefore, research activities will focus on the development of biofiltration units able to treat selected waste streams together, thus lowering space requirements, energy and additives consumption and potential sources of technical failure.

In parallel to these activities, though not directly driving the hardware development of the demonstrator, the roadmap includes research activities addressing the control of microbiological contamination within BLSS, especially with regard to the quality and safety of the food produced with fertilizer derived from human waste.

Beyond 2025

Following the construction of the BLSS demonstrator by 2025, the next phase of the roadmap focuses on validation of the system and, ultimately, on the adaptation and the qualification of the design towards use within planetary habitats. The validation phase consists of three distinct steps; technology validation, experiments with recycled urine, and cultivation tests for various crops.

Technology validation refers to the initial system checkout and functional tests to ensure the hardware meets all requirements set for the design. The subsequent experiments with recycled urine, as well as the crop cultivation experiments, will aim to fully characterize the performance of the system (focus on energy consumption, crew time) under different operating set points and with varying inputs. Of particular interest is the effect of these variations on the safety, quality and quantity of the produced biomass, as well as on the microbiome within the system.

It is envisioned that sufficient data regarding the performance, reliability and safety of the BLSS demonstrator will be available by the end of 2027 to move towards the next development phase. This final phase of the roadmap foresees the use of flight opportunities, if available, to validate various components of the BLSS demonstrator in space. Additionally, lessons learned from the validation phase will be used to optimize the design of the demonstrator and to make adaptations, as necessary, to enable it to be implemented as part of a planetary habitat. The final aim of the German Aerospace Center is to have a fully validated and flight-ready hardware design by 2030.

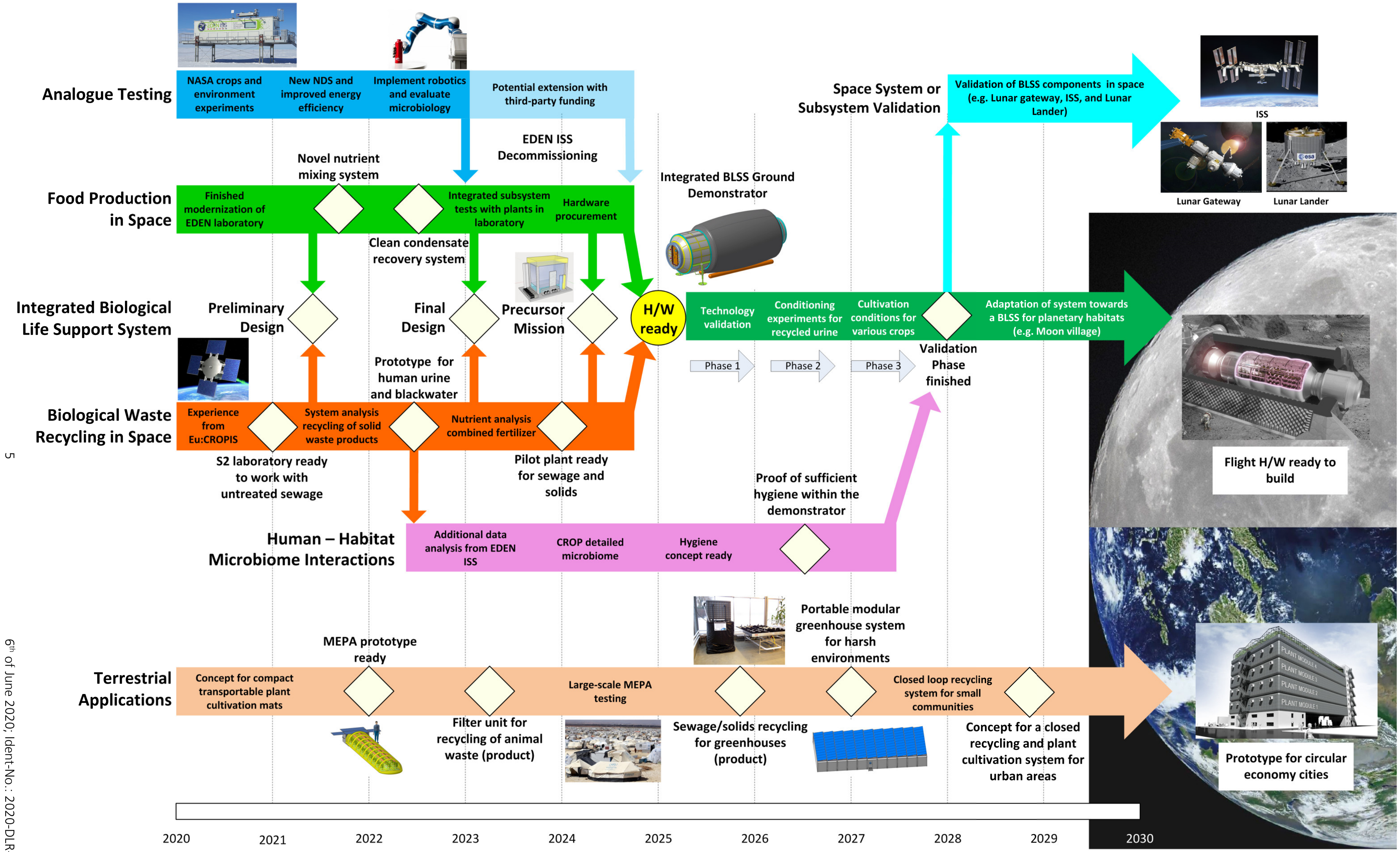

Figure 4: Roadmap for the Development of Bio-regenerative Life Support Systems within DLR (2020 to 2030). The three research fields (blue, green, orange) will result in the construction of a space-rated BLSS demonstrator in 2025. A subsequent three-year long testing phase will help validate and optimize the system. In the middle of 2022 the accompanying investigations into the microbiome of such a life support system module will start (violet) with a focus on the implications of this microbiome for crew operating the facility. Furthermore, the proposed development activities will enable additional research and development towards terrestrial applications (see the beige pathway).

Unique Testing Capabilities

Developing the envisioned space-rated BLSS module would enable DLR and the international community to meet the demands of future crewed space missions in anticipation of a return to the Moon and eventually the first human presence on Mars. An all-in-one approach is pursued, in which the BLSS module provides fresh food, oxygen and potable water to a planetary habitat infrastructure. By reducing the system to the essential aspects of plant production and waste management, the complex control relationships of an ecological overall cycle are largely eliminated. This reduction in complexity results in easier implementation.

By the year 2025, a fully integrated, space-rated ground demonstrator for Bio-regenerative Life Support Systems can provide essential contributions towards the development of a future planetary habitat infrastructure by enabling:

- **Characterization of all in- and outputs of the module (Cost/Benefit analysis)**
- **Analysis of greenhouse to habitat interfaces and humans-in-the-loop system behavior**
- **Long-term microbiome characterization**
- **Purely biological nutrient recycling with limited maintenance or resource use**
- **Flight-ready design, tested and ground qualified by 2030**
- **Spin-off possibilities towards terrestrial applications**

Although the demonstrator is only implemented as a ground test system, all subsystems and components will be designed to be compatible with a future space-qualified module. This approach will drastically reduce the necessary delta design for the final flight hardware.

For the first time, a demonstrator will enable the research community to test a combined waste recycling- and food production system with extended life support components (here: waste water recycling). As a unique selling point, realistic input relationships (e.g. required energy input, consumables, urine processing capacity) as well as output relationships (e.g. oxygen generation, food, potable water delivery) can be investigated for the first time. The interaction of the astronauts with such a system will also provide essential insights into the amount of work required (crew time) and provide a basis for a detailed microbiological investigation. The specific need for space-based BLSS is also outlined in several international roadmaps. NASA is focusing on the ARTEMIS program, by returning to Moon and establishing a sustained human presence on the surface by the year 2028. Food Production, Processing and Preservation, including bio-regenerative food systems and vegetable production systems were identified by NASA as critical mid-term technologies in the NASA Strategic Technology Investment Plan. Further, the *Global Exploration Roadmap* of the *International Space Exploration Coordination Group Technology Working Group* highlights the need for closed-loop technologies within their survey of *Critical Technologies Needs* GER-029: CLOSED-LOOP LIFE SUPPORT SYSTEMS, and GER-030: ENHANCED RELIABILITY LIFE SUPPORT SYSTEMS.

Terrestrial Applications

The production of plants with resource-efficient and space-based regenerative principles could have great impact on commercial agriculture and contribute to answering many of the 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 global food security) – even under the threat of diseases to agricultural plants, farm animals and humans.

Climate change is affecting food production through extreme weather events and desertification, causing harvest failures and destroying arable land. Modified greenhouse modules can provide an opportunity to utilize wasteland areas for agriculture and to mitigate the impact of the changing climate. Greenhouses equipped with closed-loop habitat technology excel in this purpose due to their low water requirements and emissions compared to traditional agriculture. The ability to grow crops throughout the whole year, and to minimize crop losses due to drought, pests, and diseases, makes these greenhouse modules a potential solution for agriculture in hostile climates (e.g. polar areas, deserts) as well as in remote locations (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,

and shutdowns due to pandemic diseases), 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, which saves water, fertilizer, and space, and reduces emissions, will be a key technology to secure future food supply of cities while decreasing their ecological footprints.
The C.R.O.P.®-biofilter technology can also be integrated in current farming practice to reduce nutrient losses. The treatment of livestock manure with C.R.O.P.®-biofilters results in fertilizers with reduced solids content and readily available nitrogen. These fertilizer solutions can be applied in local closed-loop systems involving alternative food or feed crops like algae cultivated in closed containments, which prevent leakage into the environment. In addition, the local production of algae and similar feed alternatives with high protein content minimizes the environmental impact of livestock farming due to reduced transportation effort and consumption of feed from environmentally harmful sources.
By linking the input/output relations the symbiotic relationship between humans and plants on Earth can be reestablished. In doing so, the food sector will be transformed from a resource diminishing one-way system into an environmentally friendly closed-loop system.

DLR Roadmap within the International Context

Developing, building, and testing a ground-based life support module, with a clear pathway towards a planetary deployment scenario, require international partners. Connecting the know-how from the global BLSS community will strengthen the overall system design, lowering general costs, and mitigating operational risks. Through cooperation, the international ambition for future human space exploration will be emphasized and overall science output maximized.

Together with its partners, it is the aim of the German Aerospace Center (DLR) to accelerate research and development in the area of Bio-regenerative Life Support Systems. A space-rated ground demonstrator is planned to be ready for testing by the year 2025.

DLR is inviting the BLSS community (universities, companies and space agencies) to partner up for this research- and development pathway. Around the world, there are a number of unique research groups, working on Controlled Environment Agriculture, waste processing, and Bio-regenerative Life Support Systems in general. Through national- and international cooperation with these research groups, by financial- and/or technical involvement, the development goals can be reached on an accelerated timeline.
Possible topics of collaboration could focus on multiple to-be-defined aspects of the demonstrator, whereas the following list outlines an initial scope only:

- Design, development, and testing of the various key subsystems within the BLSS module
- Design, development, and testing the primary structure and the deployment mechanism of the demonstrator unit
- Horticulture control systems, incorporating Artificial Intelligence (AI) and Big Data applications in relationship to CEA greenhouses
- Plant Health Monitoring, implementing visual and other sensor deployments
- Plant cultivation experiments, focusing on optimal growth parameters and conditions, and post-harvest analysis
- Psychological investigations into crew well-being
- Design of crew-machine interfacing and crew factors in relation to space greenhouses

For further information, and to establish first contact, please refer to the authors listed at the beginning of the roadmap document.