

Integration of a Photobioreactor into the MaMBA Facility as Part of a Human-centered Life Support System

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One of the most important components of a habitat for long-duration missions to Mars is the life support system (LSS), which will most likely include bio-regenerative elements. Since the lives of the crew members depend on the LSS, it is important that they can trust it. Therefore, a human-centered LSS that can be well understood and controlled by the crew is required. In this interdisciplinary work between space engineering, electrical engineering and psychology, the air revitalization component of a human-centered LSS, a photobioreactor (PBR), is being designed. This PBR is integrated into the Moon and Mars Base Analog (MaMBA) facility at the Center of Applied Space Technology and Microgravity (ZARM) in Bremen as part of a future LSS prototype. The PBR, as well as the MaMBA facility, are equipped with multiple sensors which are monitoring various environmental parameters. To provide sensor information to the crew in a preprocessed and user-friendly way, we are designing a graphical user interface (GUI) that can also be used for interaction with the PBR. All three components together, the MaMBA facility, the PBR and the GUI can then be used to test and determine human-factor-related constraints on the operation of a LSS under realistic conditions. This work presents the preliminary design of both the PBR and the GUI and gives first results on the operation of the PBR.

Nomenclature

BLSS	=	Bioregenerative Life Support System
DOX	=	Dissolved Oxygen
GUI	=	Graphical User Interface
LED	=	Light-Emitting Diode
LSS	=	Life Support System
MaMBA	=	Moon and Mars Base Analog
OD_{750}	=	Optical Density at a wavelength of 750 nm
OD_{860}	=	Optical Density at a wavelength of 860 nm
PBR	=	Photobioreactor

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PFA = Perfluoroalkoxy
PTFE = Polytetrafluoroethylene
VUI = Voice User Interface
ZARM = Center of Applied Space Technology and Microgravity

I. Introduction

For long-term missions to Mars in the coming decades, the use of physical-chemical life support systems such as these of the International Space Station is generally considered not practical, since their operation depends on supply flights[1]. These are expensive and subject to some risk of supply rocket failure[1]. An alternative could lie in using bio-regenerative life support systems (BLSS) fed with resources available on Mars, through a trophic chain where the primary producers are cyanobacteria[1]. These are capable of recycling not only food and water but also the atmosphere within a habitat, reducing crew dependence on Earth[2]. One promising cyanobacterium species for applications on Mars is *Anabaena* sp. PCC 7938 (hereafter *Anabaena* sp.)[3,4]. *Anabaena* sp. is expected to be able to grow exclusively with nutrients from the Martian atmosphere and regolith[3,4]. Furthermore, *Anabaena* sp. is suitable as feedstock for secondary producers such as higher plants[4]. In addition to these properties, that are not directly related to air revitalization of a life support system but are essential for a sustainable stay on Mars, *Anabaena* sp. is capable of producing oxygen through photosynthesis.

The photobioreactor (PBR) of the air revitalization system of a BLSS should not only produce oxygen but also be understandable by the crew as they entrust it with their lives. Therefore, a reliable interaction between the LSS and the crew is needed. Within the project "The Living Habitat" at the University of Bremen, human-centered technologies are being developed and investigated so that they together with a human crew lead to a safe and successful stay on Mars. Therefore, a PBR as an LSS component is being integrated into the MaMBA laboratory which has been built at the Center of Applied Space Technology and Microgravity (ZARM) as a prototype of a lunar or Martian habitat. The PBR shall be able to respond to varying needs of the crew, in particular to that of maintaining a stable atmospheric composition despite varying load levels. This requires a buffer system based on the photobioreactor, that is capable of responding quickly to changes inside the habitat. In order to monitor both the habitat and the photobioreactor an interactive sensor network is being developed that provides information to the crew in a user-friendly way. Since both habitat technologies, the PBR and the sensor network, are interacting with the crew, the habitat technologies and the crew are considered as members of the same human-agent team. The processes in those human-agent teams are also being investigated within the project. One important aspect of a reliable interaction between habitat and crew is the use of a graphical user interface (GUI) that connects the three components of the “Living Habitat”: The PBR, the sensor network and the human crew. Its task is to enable the human crew to monitor and control the LSS in an intuitive and understandable way.

In this study we use a photobioreactor that produces oxygen by cultivating the cyanobacterium *Anabaena* sp. as a test case for a life-critical system that the crew (in this case: our test subjects) need to operate efficiently. For this purpose, an experiment is being set up in which compressed air is continuously fed into the photobioreactor to enable the conversion of carbon dioxide into oxygen by photosynthesis. To monitor changes in carbon dioxide and oxygen, both concentrations are being measured in the gas outlet of the PBR. For the processing and visualization of the data recorded during the experiment, and for interacting with the PBR a GUI is being developed. First results are presented here.

II. Set-up and methods

Since the PBR is a central element of the habitat’s BLSS, the PBR system developed in this study is explained in Section A. The control unit which is used for monitoring and controlling the PBR is described in Section B. The first considerations for the GUI, which shall be used for interaction between humans and the PBR and is directly connected to the control unit, is described in Section C.

A. Photobioreactor system

1. Requirements for the overall system

Like that of any other microalgal species, the growth of *Anabaena* sp. is affected by various parameters. These include temperature, light intensity, pH and the availability of nutrients[5]. Although *Anabaena* sp. is capable of growing with nutrients from the Martian atmosphere and regolith[4], in this case it is fed with $BG11_0$ medium and pressurized air because the LSS is designed to revitalize the air inside the habitat, which has approximately the same composition

as the Earth's atmosphere. These parameters must be kept within ranges which support the vigorous growth of *Anabaena* sp. The values of the growth parameters that are selected for the experiments are shown in Table 1.

Table 1: Growth parameters chosen for cultivating *Anabaena* sp.

Parameter	**Value**
Temperature	30°C
Light intensity	80 µmol/(m^2·s)
pH	7 - 10
Growth medium	$BG11_0$
Air composition	Ambient air (78.1 Vol.%, 20.9 Vol. % O_2, 0.04 Vol.% CO_2)
Light temperature	Warm white light

To monitor the growth and the metabolism of *Anabaena* sp., selected parameters shall be measured throughout the entire experiments. These include the temperature and the pH of the growth medium, the dissolved oxygen (DOX) and the optical density (OD) inside the liquid phase of the PBR and the concentrations of carbon dioxide and oxygen inside the outlet air stream of the PBR. Based on the measurements of the pH and the temperature, these parameters shall be controlled to keep them in the range given in Table 1. In addition, the OD shall be controlled.

To make the cultivation of *Anabaena* sp. reproducible and to avoid loss of the culture due to contamination, an axenic culture shall be used for the experiments. For this purpose, sterilization of all components in contact with the cultivation medium is necessary. The MaMBA module is already equipped with microbiology equipment, including an autoclave which is used for the sterilization of the components. The inside of the autoclave has the dimensions 265 mm x 465 mm, which dictates the maximum dimensions of the photobioreactor[6]. Autoclaving also dictates requirements on the materials of the PBR. These must be resistant to temperature up to 121°C. Inasmuch as possible, materials shall have similar coefficients of thermal expansion. In cases where this is not possible, design measures must be taken to avoid stresses due to different thermal expansions[7]. Another requirement for the materials is the resistance to corrosion due to electrochemical processes between different metals.

The geometry of the photobioreactor results from the idea of integrating the life support system of the MaMBA habitat into its walls in the long term, in order to save space inside the habitat on the one hand, and to protect the crew from space radiation through the water inside the reactors on the other[8,9]. Flat panel photobioreactors are best suited for this requirement.

Figure 1. Exploded view of the PBR. *At the front and back, an O-Ring, a polycarbonate sheet and a silicone gasket (in this order) are pressed into the inner frame by an outer frame. At the bottom, the sparger seal and perforated membrane (in this order) are pressed into the inner frame by the sparger.*

2. Structural design

The core element of the experimental setup is the flat panel PBR itself. Overall, the PBR holds a volume of approx. 2.9 l which is derived from the cultivation chamber's internal dimensions of 377 mm x 170 mm x 48 mm. The external dimensions of the PBR are 442 mm x 220 mm x 80 mm, allowing it to fit into the existing autoclave. The PBR, shown in Figure 1, consists of an inner frame, two O-rings, two side walls, two silicone gaskets, two outer frames, a sparger, a sparger gasket and a perforated membrane. Pressurized air is supplied to the PBR through the latter, to ensure uniform gassing within the PBR. This ensures adequate gas exchange and mixing of the cultivation medium. On Mars only partial gravity prevails, which affects the hydrodynamic properties of the PBR. However, this is not considered in this phase of the

project. As shown in Figure 1, the side walls are pressed into the inner frame using the outer frames. The outer frames are connected to the inner frame using screws. The recesses of the inner frame, where the side walls are inserted, feature tracks for an O-ring which seals the cultivation chamber. Another recess is located on the underside of the inner frame. The sparger is pressed into this, also with the aid of screws, together with the sparger seal and the perforated membrane. In addition to the recesses for the side walls and the sparger, the inner frame has several connections on the top and on the side. The side has connections for two sensors and two ball valves which serve as the inlet and outlet for the cultivation medium, respectively. In addition, there are two ports on the side where a bent stainless steel pipe, through which water flows for temperature regulation is connected. Connections for two more sensors are also provided on the top. Furthermore, there are connections for a 3-way port and the gas outlet. Behind the gas outlet is a sterile filter to prevent contamination of the environment by cyanobacteria. Three other ports are found on the bottom of the sparger, only one of which is used for the gas inlet. A ball valve and a check valve are located at the gas inlet to prevent backflow of the cultivation medium into the gas supply line when the PBR is set up or disassembled, or when the gas supply is interrupted, and a sterile filter prevents contamination of the cultivation medium by impurities in the supply air.

The inner frame and the sparger, which are in constant contact with the cultivation medium, are made of stainless steel 1.4044 as this alloy is significantly more resistant to corrosion than other alloys[7]. In contrast, the two outer frames are made of aluminium EN AW-6061 since a lightweight material is required here that nevertheless has sufficient strength to hold the two side walls in the inner frame[7]. These side walls are made of polycarbonate as this material has a high transmittance to light (86%) and is much more shatterproof than glass[10], making it easier and safer to handle. However, polycarbonate is susceptible to scratching so a silicone gasket is needed between each of the side walls and the outer frames[7]. The perforated membrane, the sparger seal, and the two O-rings that sit between the side walls and the inner frame are made of Viton®. The air filters are made of stainless steel 1.4404, Viton® and a polytetrafluoroethylene (PTFE) membrane. The ball valves and the check valve are made of stainless steel 1.4404. For the gas lines, only stainless steel 1.4401 or perfluoralkoxy (PFA) tubes, which have a low permeability to carbon dioxide and oxygen compared to other plastics[11], are used. All tubes through which either the cyanobacterium-containing cultivation medium, or the heating water, are transported, are made of silicone.

3. Photobioreactor periphery

Although the PBR is to be integrated into the walls of the MaMBA habitat in the long term, it is currently installed in one of the racks. This has the advantage that the experimental setup is more flexible and its components are more accessible. In addition, in the event of a water leak, the wooden structure in the walls of the MaMBA habitat will not be damaged. The experimental setup inside the rack, including the PBR and its periphery, is shown in Figure 2.

Each time before starting the experiment, the light-emitting diode (LED) panel (Tiron Service GmbH & Co. KG) which is positioned right behind the PBR must be recalibrated due to its degeneration over time. For the experiments, warm white light with a light intensity of 80 µmol/(m^2·s) is used. Currently, the light intensity is tuned by adjusting the number of rotations of a potentiometer. The light intensity is verified with help of a quantum sensor (Apogee MQ-200X, Apogee Instruments, Inc.).

To start operation, 2.75 l of $BG11_0$ medium are first pumped from the supply bottle into the PBR using a peristaltic pump (EZO-PMP-L™, Atlas Scientific, LLC). The PBR is inoculated with a cyanobacterium suspension through one of the lines of the 3-way port. The inoculum has a volume of approximately 150 ml and a cell density such that the initial OD_{750} of the culture inside the PBR is 0.05 (ca. $2 \cdot 10^8$ cells/ml). A quick coupling connected in the direct vicinity of a Bunsen burner is used for this purpose. During inoculation, it must be ensured that the gas supply is interrupted as otherwise the inoculum can only flow into the PBR to a limited extent due to the increased pressure in the PBR.

After inoculation, the gas supply can be switched on again. The compressed air supplied to the PBR comes from the compressed air network of the ZARM and is first passed through a service unit consisting of a fine filter, a microfilter, a pressure reducer and an oil separator. The cleaned air is then passed through another pressure reducer in which the pressure is reduced to the rotameter's operating pressure of 1.3 bar (absolute). The rotameter is used to set a flow rate between 0.35 and 3.4 l/min which first flows through the sterile filter, the check valve and the ball valve at the gas inlet, and then enters the PBR through the sparger. After passing through the PBR to ensure a proper mixing of the cultivation medium and gas exchange, the air exits the PBR through the sterile filter on the top of the PBR.

Since the evolution of carbon dioxide and oxygen shall be monitored during the experiment, the concentrations of both carbon dioxide (EZO-CO2™, Atlas Scientific, LLC) and oxygen (EZO-O2™, Atlas Scientific, LLC) in the exhaust air, as well as its temperature and relative humidity (EZO-HUM™, Atlas Scientific, LLC) and the gauge pressure (EZO-PRS™, Atlas Scientific, LLC) are measured downstream of the air outlet. Since the sterile filters and the sensors are sensitive to condensate, the exhaust air is dried twice. First, the air is cooled directly at the air outlet with an autoclavable air cooling unit operated with cooling water to prevent clogging of the filter. The remaining moisture in the air is removed using silica gel before entering the measuring unit. This gel does not adsorb carbon dioxide and can be regenerated with a drying oven[12]. It gets saturated after about four days, so it has to be renewed and regenerated. After the measurements, the gas flows through a check valve out of the measuring unit and into the environment. In addition to gas-related parameters, the pH (EasyFerm Plus PHI Arc 120, Hamilton Bonaduz AG), temperature (TH-21, OMEGA Engineering GmbH), DOX (OXYPro® WR, PreSens Precision Sensing GmbH) and OD_{860} (Dencytee RS485 120, Hamilton Bonaduz AG) are continuously measured inside the cyanobacterial culture. In order to facilitate the scalability of the whole system in the long term (e.g., connecting multiple PBRs), an in-house OD sensor is currently being developed that can be installed between several PBRs. This consists of a flow-through cell in which the light absorption is measured.

Figure 2. Experimental set-up including the first configuration of the PBR and its periphery. *With the help of the peristaltic pumps, either fresh medium is pumped into the reactor or cell suspension is pumped out of it, into the harvest bottle (1). The air for gas exchange and mixing is fed into the PBR from the bottom (2). Cooling/heating water is pumped through the bent stainless steel pipe (3) for temperature regulation. During the process, the parameters in the cyanobacteria suspension (4) and in the gas outlet (5) are measured continuously. All sensors and actuators are connected to the data processing unit (6). Either an acidic solution or a basic one (7) can be pumped into the PBR for pH regulation.*

To grow the culture under approximately constant conditions, the temperature and pH of the growth medium, as well as the OD, can be controlled. While the temperature is automatically controlled by a thermostat (DC50-K41, Thermo Haake®) that pumps cooling or heating water through the stainless steel tubes inside the PBR, the pH and OD are controlled manually via the data processing unit. The flows to and from the PBR are shown in Figure 3. The pH of the medium can be adjusted with a basic or an acidic solution, as needed, by pumping a small amount of either solution from the supply bottle into the PBR with a small peristaltic pump (EZO-PMP™, Atlas Scientific, LLC). However, a different control logic is applied to the OD. When a certain OD is reached, cell suspension is first pumped from the reactor into the harvest bottle which has a capacity of 5 l with the help of another persitaltic pump (EZO-PMP-L™, Atlas Scientific, LLC). Then, the same volume of fresh cultivation medium is pumped from the storage bottle into the PBR which still contains 2.25 l of $BG11_0$ medium after starting the experiment. Since there is no automatic control of the cell density yet, the volume with which the medium is to be diluted is first calculated manually in order to achieve the desired OD. The aim is to approximate a turbidostat. The

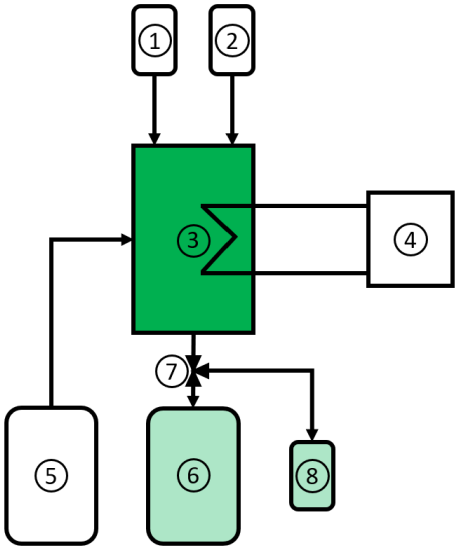

Figure 3. Scheme of the flows of the PBR. *To regulate the pH, either an acid solution (1) or a basic one (2) is pumped into the PBR (3). The temperature is controlled by a thermostat (4). For controlling the cell density, fresh medium (5) can be pumped into the PBR and cell suspension can be pumped into the harvest bottle (6). The three-way valve (7) in front of the harvest bottle can be used to divert the cell suspension into a small sample bottle (8).*

same peristaltic pump that pumps the biomass from the PBR is used for sampling. A three-way ball valve sits in front of the actual harvest bottle which is used to divert the cyanobacterial solution into a small sample bottle with a capacity of 50 ml. The sample can then be taken from it with minimal risk of contamination. This allows sampling without interrupting the actual cultivation process.

4. Startup and sterilization

The operation of the PBR starts with cleaning and sterilization procedures. These must be performed for all components that come into contact with the cultivation medium or the process gas and are also located between the two sterile filters at the gas inlet and outlet. Since the existing autoclave has to fit into one of the racks in the MaMBA module, its dimensions are predetermined. Consequently, not all the components required for operating the PBR fit together in the autoclave, so several autoclave runs have to be carried out. After autoclaving all components, a laminar flowhood is used to assemble the PBR and its periphery under sterile conditions so that the risk of contamination is minimized. After sterile assembly, the PBR with its periphery is integrated into the rack and connected to the gas supply, gas analysis and temperature control. Furthermore, all sensors are connected to the data processing unit.

B. Control system

1.Sensors and actuators

The sensors and actuators that are used to monitor and control the cyanobacterial metabolism and the growth conditions inside the PBR are listed in Table 2. All listed sensors and actuators except the thermostate, which is a stand-alone unit so far, are connected to the data processing unit either via I^2C interface or via analog output. While the sensors that are monitoring the growth environment are located inside the liquid phase of the PBR, the gas sensors which measure the metabolic activity of *Anabaena* sp. are located outside the PBR to avoid a need for sterilization.

Table 2: Sensor and actuator specifications.

Function	Model and company	Measuring principle	Amount	Range	Accuracy
pH measurement (liquid)	EasyFerm Plus PHI Arc 120, Hamilton Bonaduz AG	pH potential measured against reference	1	0 to 14	± 0.05
Temperature measurement (liquid)	TH-21, OMEGA Engineering GmbH	Measurement of temperature-dependent electrical resistance	1	-50 to 200 °C	± 0.2 °C (between 0 and 70°C)
Dissolved oxygen measurement (liquid)	OXYPro® WR, PreSens Precision Sensing GmbH	Electro-optical measurement	1	0 to 45 mg/l	± 0.04 mg/l (at 9 mg/l)
Optical density measurement (liquid)	Dencytee RS485 120, Hamilton Bonaduz AG	Transmission and reflection measurement at wavelength of 860 nm	1	0 to 200 g/l	± 0.05 g/l (between 0 and 10 g/l)

Oxygen measurement (gaseous)	EZO-O2™, Atlas Scientific, LLC	Electro-chemical measurement	1	0 to 42 %	± 0.01% ± 0.01 ppm
Carbon dioxide measurement (gaseous)	EZO-CO2™, Atlas Scientific, LLC	Nondispensive infrared gas detection	1	0 to 1000 ppm	± 5% ± 50 ppm
Temperature and relative humidity measurement (gaseous)	EZO-HUM™, Atlas Scientific, LLC	n.s.	1	0 to 100 %*	± 2%
Pressure measurement (gaseous)	EZO-PRS™, Atlas Scientific, LLC	Piezoelectric measurement	1	0 to 50000 psi	± 2%
Control of pH	EZO-PMP™, Atlas Scientific, LLC	-	2	0.5 to 105 ml/min	± 1%
Control of medium flow	EZO-PMP-L™, Atlas Scientific, LLC	-	2	10 to 750 ml/min	± 2 % ± 2 ml
Control of cooling/ heating water	DC50-K41, ThermoHaake®	-	1	-40 to 150 °C	± 0.01 °C

*No specification for temperature measurement.

2. Data processing unit

To monitor the system as well as interact with different actuators, an in-house data processing unit is used which is a derivation of the sensor system used inside the MaMBA module. The data processing unit is shown in Figure 4. The advantages of such an in-house data processing unit are scalability, adaptability to the needs of the PBR, flexibility and low cost.

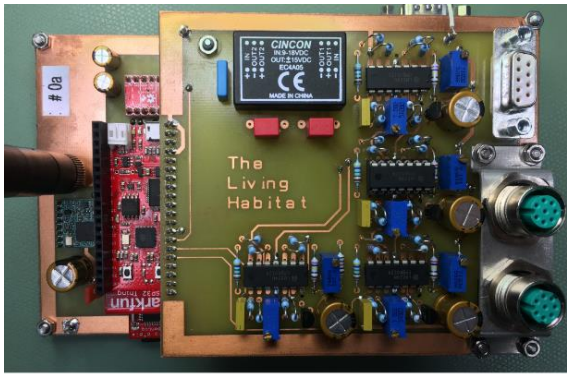

Figure 4. Data processing unit of the PBR. *The sensors and actuators are connected to the data processing unit either via I^2C interface or via analog output.*

The control system developed at the ZARM consists of a sensor board to which all sensors and actuators are connected and a RaspberryPi which receives data from the sensor board and communicates with the backend. The sensor board is based on two ESP32 microcontrollers that can communicate with each other by using a custom 3-wire communication protocol. One microcontroller controls the actuators and can later be used to implement different control mechanisms. The data required for those is provided by the other microcontroller that reads data from the sensors connected to it. Data is read cyclically and checked for values exceeding threshold limits given by the growth conditions in Table 1. If a threshold limit is exceeded, data is sent immediately, otherwise it is sent after a delay (~15 s). Data is sent from the sensor boards to the RaspberryPi using LoRa. The RaspberryPi is used as a central receiver that saves the received data locally and sends it to the backend, hence ensuring redundancy in data. From the backend, data can be accessed by the GUI that is discussed in Section C, or other users, or software, in order to process and analyze it. In addition, the RaspberryPi can act as a receiver for more than one sensor board. The adaptability is restricted by the number of sensors connected to the ESP32. The same applies for the controlling ESP32.

C. Graphical user interface

1. *System architecture*

The system architecture, shown in Figure 5, is based on an MQTT broker which distributes measured data from sensor boards inside the MaMBA module and the PBR to relevant applications. The MQTT broker and database reside in the ZARM virtual machine. Measured data is transmitted wirelessly to the RaspberryPi, from where it is subsequently transferred to the MQTT broker via Ethernet. Applications only require a subscription to the MQTT broker to gain access to the relevant information. This approach facilitates efficient data transfer and management, ensuring that data from the sensor boards is accessible to relevant applications in a timely and secure manner. By leveraging the capabilities of MQTT broker technology and wireless transmission, the system is able to support effective data distribution in a manner that is both scalable and reliable.

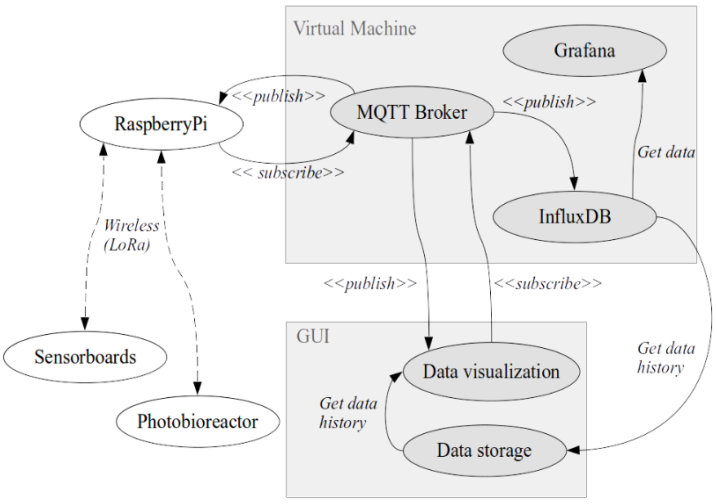

Figure 5. System architecture of the PBR's GUI. *Data from the habitat sensor boards and the PBR's data processing unit are sent to the RaspberryPi and the MQTT broker which distributes it to relevant applications such as the database and GUI. In addition, data can be sent back from the GUI to the PBR's data processing, e.g. for setting control values.*

For the GUI implementation, a Python application is used. Generally, an installed application is able to make full use of the computing power of the end device, ensuring optimal performance and a responsive interface[13].When it comes to building desktop applications in Python, a number of libraries are available, such as PyQt6, PyGTK, wxPython, and Tkinter. The Python application is being developed using PyQt6, which is a highly effective library for building desktop applications. It offers a wide range of customizable widgets, tools and features that enable developers to create highly functional, attractive and responsive GUIs. Moreover, PyQt6 is cross-platform, meaning that applications can be developed on one platform and then deployed on others without any significant modifications. PyQt6 also has extensive documentation, making it easier for developers to learn and use the library effectively[14,15].

2. *Design considerations*

Since the crew of a space mission could not survive without the LSS, it is of utmost importance that the crew can trust the system and rely on it. For this reason, the LSS needs to be developed with the consideration of the human crew from the very beginning. Furthermore, it needs to function as autonomously as possible as the crew has to work on numerous tasks and does not have the capacity to constantly monitor the LSS. A growing body of literature suggests that such an autonomous technical system could even be considered a further team member[16] as it is taking over a wide range of tasks normally carried out by humans, instead of just one function like typical automation[17]. A first psychological experiment within another subproject of "Living Habitat" aims to investigate how an artificial agent presented as a team member instead of a tool influences trust and affect towards this artificial agent. First, human subjects are introduced to the artificial agent through a description. After a short familiarization phase their task is to repair the LSS with verbal instruction from the agent. So far, we are using a PBR mockup and a voice user interface (VUI). For further experiments and the LSS in general we aim to have the GUI in addition. This provides redundancy, which is a requirement in such a safety-critical system as the LSS. Moreover, the two different interfaces also use different modalities (auditory vs. visual perception) which, depending on the task, help to ensure that resources do not overlap with another task during usage[18]. To sum it up, the VUI but even more the GUI are crucial for an understandable BLSS that is reliable and is perceived as such by the crew.

Herefore, the GUI requires a clear presentation of data, grouping of correlating values and notification of atypical situations. The GUI has to be designed user-friendly and accessible to a wide range of users with a focus on presenting data in a manner that is easily understandable. Where applicable, Ten Usability Heuristics[19] and The Eight Golden Rules of Interface Design[20] are utilized as a base for the general design of the GUI. The GUI also includes features such as audio and visual notifications of atypical situations and buffering of data for a certain period of time for faster

access. If data is required outside the specified time period, it can be retrieved from the database. This also enables the program to load and display recent data right after a software restart.

To ensure that crew members are able to understand and respond to emergency situations, the GUI is designed to address a wide range of user groups. Different statuses of the system and its sub-systems are color-coded so that non-expert users can easily assess the general situation while also allowing for more in-depth analysis for those who are familiar with the system. To address the issue of managing and presenting large amounts of data, a drill-down principle is employed which allows for the explicit data to be pushed into the background while still being accessible. The current overall system status is diplayed on the home screen. In addition, an image representation of the MaMBA module is displayed where individual areas such as the floor or sensor boards or the PBR are visually differentiated. Clicking on an area provides access to detailed information. This approach facilitates efficient data management and enhances user experience by minimizing information overload and improving accessibility.

With a focus on user-friendly design, accessibility and comprehensibility, the GUI aims to enable crew members to monitor the habitat and PBR effectively, respond to abnormal situations and take steps to ensure the safety and well-being of all crew members.

III. Results and discussion

A. Lessons learned

Two test runs of five days each with the initial PBR configurations were conducted in December 2022 and February 2023, respectively, in order to determine construction and operational constraints. The lessons learned from the first test runs and the corresponding countermeasures are described in this and the following section.

One of the main problems during the test runs was the high evaporation in the PBR which led to condensate on the hydrophobic PTFE filter membrane and the gas sensors. Due to the accumulated condensate on the hydrophobic PTFE filter membrane, the outlet filter became clogged during the course of the experiment, resulting in an increase in pressure in the PBR and a decrease in airflow into the PBR. The condensate caused by the high humidity also led to measurement errors in the gas sensors.

Another cause of possible measurement distortions of the gas sensors is the changing solubility of carbon dioxide and oxygen in water depending with temperature. For this reason, care must be taken to ensure that temperature fluctuations in the medium are less than 1 K[21].

Not only the gas sensors, but also the liquid sensors (OD and DOX sensor) delivered incorrect measured values in the first test runs. Originally, both sensors were screwed into the PBR from above, as shown in Figure 6, which caused gas bubbles to settle in the measuring range of the sensors and falsified the measurement result.

Figure 6. First configuration of the PBR. *Here, the OD and DOX sensors are screwed from the top, causing gas bubbles to settle in the measurement area of the sensors.*

In addition to the problems with the sensors, there were problems with the actuators, especially with the large peristaltic pumps. Due to current peaks during operation of the motor, the control electronics of the pumps failed permanently despite subsequent improvements.

Other problems mainly concerned the design of the PBR. Above all, leaks occurred during the first test runs. The first leak which was noticeable by the dripping of culture medium was at the two blind plugs in the sparger. To avoid having to stop the test the area was sealed with silicone grease, although this could contaminate the culture. The second leak was at the screw-in fittings inside the PBR to which the stainless steel tube for temperature control is connected. This leak could only be found after the culture medium in the PBR continued to rise due to the addition of cooling/heating water. To prevent the PBR from overflowing, the temperature control had to be stopped during the experiment. Both leaks could be traced to damage, during autoclaving, of the Teflon tape used as a sealant.

B. Improved configuration

The goal of the experiment with the improved configuration is to fix the issues of the initial configurations and to obtain a proof of concept, that means cultivating cyanobacterial biomass with the designed PBR.

To prevent clogging of the outlet filter and failure of the gas sensors in the improved PBR configuration, the air is now dehumidified after leaving the PBR. For this purpose, an autoclavable stainless steel air cooling unit powered by cooling water was built and is installed on the PBR. After the air has been cooled in the cooling unit, it is passed through a bottle where the condensate is collected. The sterile filter is now located at the outlet of the condensate collection bottle so that only dried air is passed through. In addition, a silica gel-based drying unit is used to remove any residual moisture in the air before it is passed through the measuring unit. The false readings of the OD and DOX sensors caused by gas bubbles were corrected by integrating the two sensors from the side, as shown in Figure 7. This prevents gas bubbles from being trapped in the measurement area since the gas bubbles flow through the measurement area instead of being trapped inside it. The large peristaltic pumps have been repaired by designing a separate control electronics which was integrated on the sensor board to enable error-free operation of the pumps, and the leakage problem was solved by using O-rings as a sealant instead of Teflon tape.

Figure 7. Improved configuration of the PBR. *To avoid condensate on the gas sensors and the PTFE filter membrane, a gas drying unit is attatched to the gas outlet of the PBR. In addition, the DOX and OD sensors are mounted on the side to avoid measurement interferences due to gas bubbles. Shown here is the PBR after 160 hours with an OD_{750} of 1.37.*

C. System verification

The third experiment was conducted in April 2023. In addition to the cultivation parameters stated in Table 1, a flow rate of 0.35 l/min was used for gassing of the PBR. The cultivation mode in the experiment is batch, i.e. the culture is not diluted and the pH is not regulated, to obtain a baseline experiment without external influences triggered by control mechanisms for comparison with future experiments. The experiment lasted about eight days (186 hours). The growth of the culture was measured both (every 15 s) with the OD sensor inside the PBR (OD_{860}) and, daily with one exception, with a spectrophotometer (OD_{750}). Results are shown in Figure 8. The measurements, in particular of the OD_{750}, indicate a typical growth curve for cyanobacteria: The growth starts with a lag phase from Hour 0 to 40 where OD_{750} is approx. 0.05. This phase is followed by an exponential phase from Hours 40 to 160 with a maximum growth rate of 0.038 h^{-1}. Growth then slows down, presumably entering a linear (light-limited) phase. The maximum OD_{750} during the experiment is reached on Hour 186 and is 1.73. The automated OD measurements are less accurate than the measurements acquired with the external spectrophotometer. This is presumably due to the resolution used, as can be seen from the step-like progression of the OD_{860}. Nevertheless, the recorded OD_{860} evolution is simular to that of the OD_{750}. Although the pH was not regulated

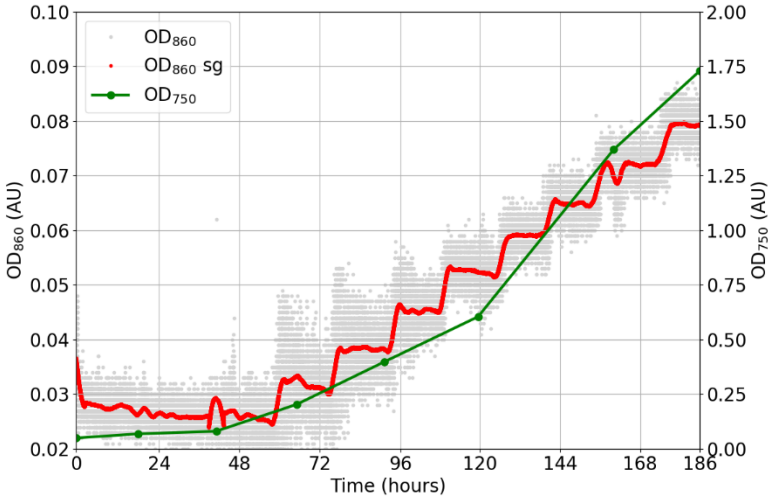

Figure 8. Course of OD_{750} and OD_{860} during the eight-day experiment with the improved configuration. *In particular, the measurements at OD_{750} are indicating a typical growth curve for cyanobacteria. Although the measurements OD_{860} are less acurate, they have a similar progression to the measurements at OD_{750}. sg: Savitzky golay filter with window size 1000 and polynomial order 2.*

during the batch experiment, it varied little after Hour 72, when it remained between 9 and 9.5 (see Figure 9a).

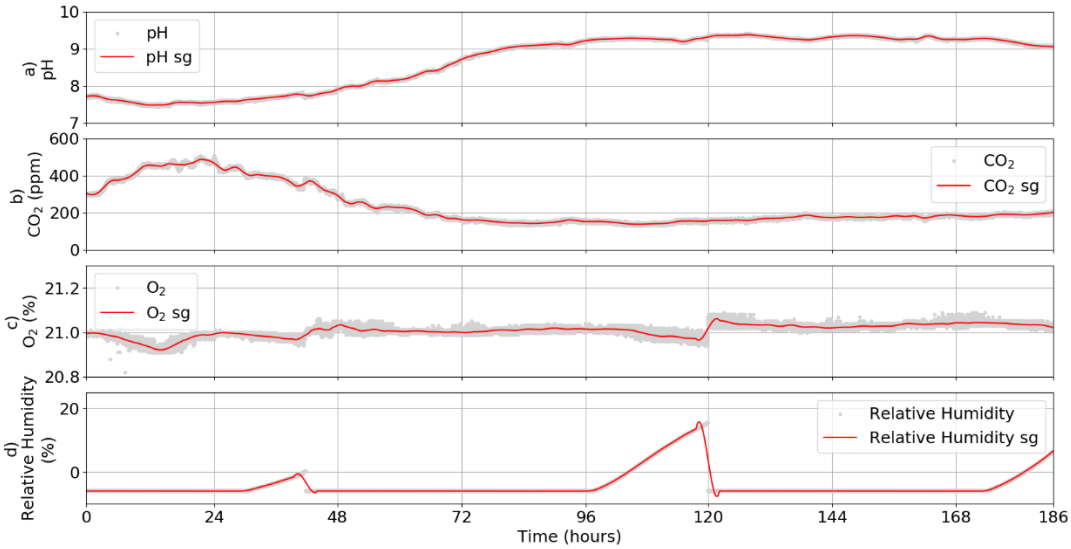

Figure 9. Gas and pH measurements during the eight-day experiment. *The pH (a) increases during the first 72 hours, but remains constant thereafter. The carbon dioxide concentration (b) shows a general decrease during the experiment. The oxygen concentration measurements (c) seem to be influenced by the silica gel drying unit as the oxygen concentration decreases as soon as the silica gel is saturated, i.e. the relative humidity (d) increases. sg: Savitzky golay filter with window size 1000 and polynomial order 2.*

The carbon dioxide concentration in the gas stream decreases after Hour 24, as shown in Figure 9b. This trend can be attributed at least in part to carbon fixation by the cyanobacteria, although other external influences cannot be ruled out, especially considering the initial low carbon dioxide concentration and its increase during the first day. At present, it is not clear where this effect comes from, but future experiments will show whether it can be replicated. Figures 9c and 9d suggest that the use of silica gel, to dry the air before it enters the measuring unit, affects the oxygen concentration. Comparing the course of oxygen concentration and relative humidity in the gas stream, it seems that the oxygen concentration decreases as soon as the silica gel is saturated, i.e. the relative humidity increases. In contrast, the oxygen concentration increases again immediately after the saturated silica gel has been replaced, for example on Hours 48 and 120. An exception is the decrease within the first 24 hours, which could be attributed to the missing temperature compensation (only from Hour 48) of the oxygen sensor. In order to minimize external influences on the carbon dioxide and oxygen measurements, such as possible fluctuating gas concentrations at the gas inlet due to the compressed air network of the ZARM, the PBR will be fed with compressed air from a gas cylinder in the next test so that the concentration at the gas inlet remains constant. In addition, the silica gel drying unit will be removed since the air cooling unit operated with cooling water should already dry the air sufficiently.

IV. Conclusion and outlook

In this work, a PBR was designed and integrated into the MaMBA habitat as an air revitalization component of an LSS. An associated GUI is under development, so as to make the status of such a technical system more intuitively understandable for humans. In the experiments conducted with the photobioreactor so far, no oxygen production by cyanobacteria could be measured because some challenges had to be handled first. Among these were mainly incorrect readings due to gas bubbles, condensate or isolated leaks. In addition, gas measurements were likely affected by external influences. Nevertheless, the PBR design is promising as the system itself worked and vigorous growth was recorded. Based on the findings of the first experiments, some adjustments will be made, especially regarding gas measurement, so that the metabolic activity of *Anabaena sp.* can be characterized more thoroughly in the upcoming experiments. In the long-term, this study will serve as a basline for further characterisation of the PBR as well as for the development of an air revitalization system for habitats beyond Earth.

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