

# Modeling, Design and Simulation of a Reconfigurable Aquatic Habitat for Life Support Control Research

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This paper presents the design, modeling, and simulation of a reconfigurable aquatic habitat for experiments in regenerative life support automation; it supports the use of aquatic habitats as a small-scale approach to automation experiments relevant to larger-scale regenerative life support systems. The habitat consists of a ten-gallon tank with four compartments, containing animal and botanical elements. The water volume serves as the medium through which life-support compounds, like oxygen, are transferred between organisms. A motorized hatch allows reconfiguration of the system to allow or prevent the exchange of gases with the atmosphere, and enables the study of fail-safe automation mechanisms. Sensors and actuators measure and intervene to regulate life support variables in the water. The model serves as an analytical reference for future tests in hardware settings, and to test advanced control architectures and policies that enable the system to operate safely and with increasing levels of autonomy, allowing for human intervention if necessary. The goal of the aquatic habitat is to enable life support control concepts that may be challenging to test in larger-scale life support systems. The mathematical description of the dynamic model of the system is presented in this paper with results from simulations of a distributed control approach applied to the habitat.

## I. Introduction

This paper builds on the use of aquaria, or aquatic habitats, as small-scale platforms for Earth-based and spaceflight life support systems (LSS) research<sup>1</sup> and applications.<sup>2</sup> Their reuse of a limited volume of water and their capacity to support life forms, such as aquatic animals and plants, make them a candidate for the study of sustainability attributes of larger-scale environmental systems. Aquaria may involve biological processes, such as photosynthesis, that regenerate life support resources, such as oxygen. This makes them an attractive option for research on bioregenerative life support systems (BLSS). In particular, this project focuses on their application for experiments in life support control and automation, pertinent to the study of concepts and strategies that may be difficult to test in larger-scale BLSS. The objective of this paper is to describe the design, mathematical modeling, and simulation of an aquatic habitat with the aim to serve as a numerical testbed for life support control and automation research. Although the model presented here only reports results based on simulations, hardware of the system described is used to identify model parameters.

### A. Background

Past experiences reported in the literature make use of aquatic habitats for experiments in zoology and physiology in low Earth orbit (LEO),<sup>3-7</sup> and for ecotoxicological studies in ground-based experiments.<sup>2,8</sup> The results obtained in LEO during Space Shuttle missions STS-89 and STS-90 show that microgravity does not affect aquatic habitats considerably for exposure periods of up to 16 days.<sup>4</sup> These experiments were conducted with the Closed Equilibrated Biological Aquatic System (CEBAS) minimodule, which also flew in STS-107.<sup>6</sup> No results were reported from this last flight due to the accident of the Space Shuttle Columbia. A renewed initiative, this time by the Japanese Aerospace Exploration Agency (JAXA), has been planning

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to include an aquatic habitat in their International Space Station module, Kibo.<sup>9</sup> Beyond these efforts, very little has been done to make use of aquatic habitats for research in spaceflight life support control and automation.

## B. A Novel Approach to the Use of Small-Scale Aquatic Habitats

The project described in this paper may be framed within the discipline known as *biospherics*.<sup>1</sup> In short, the field is said to aim for the goals of: (1) building models of terrestrial ecosystems to better understand the processes that regulate life; (2) building habitats to extend the human presence to extreme environments on Earth and beyond; and (3) developing technologies that may help to utilize natural resources efficiently and in a more sustainable way.

The approach of this project addresses these goals by making use of an aquatic habitat to: (1) study the balance or homeostasis of small-scale ecosystems that contain a combination of natural agents (organisms) and artificial agents (controllers); (2) investigate the integration and automation of life support processes for artificial habitats; and (3) help develop technologies that may increase the sustainability of environmental and production systems on Earth.

Given the focus in life support control research, the main goal of the project hence becomes to determine how artificial agents (automation technology among others) may help to: (1) increase the sustainability of environmental systems; and (2) help reduce the stored mass of consumables in controlled ecological life support systems (CELSS).

## C. Preliminary Description

The model presented in this paper centers on the process of respiration, in which  $O_2$  is consumed by organisms while exhaling  $CO_2$  as a by-product. Plants help to regulate the concentration of  $CO_2$  through the photosynthesis process, in their case producing the oxygen needed by the consumers and aiming to maintain acceptable gas concentration levels in the habitat. In the case of the aquatic habitat, water serves as the medium in which these quantities are stored (dissolved), and through which they are exchanged between the organisms.

The habitat used in this project consists of a 10-gallon tank divided in four compartments by three separators; the separators allow the water to flow between the compartments. The first and second compartments contain animals (consumers) and plants (producers), respectively. The third compartment contains media that serves the purpose of mechanical, chemical and biological filtration. The fourth compartment allows access for sensors and water pump. The sensors used include dissolved oxygen (DO) and pH. The water flows continuously along the four compartments, recirculating from the fourth compartment back into the first as shown in Fig. 1.

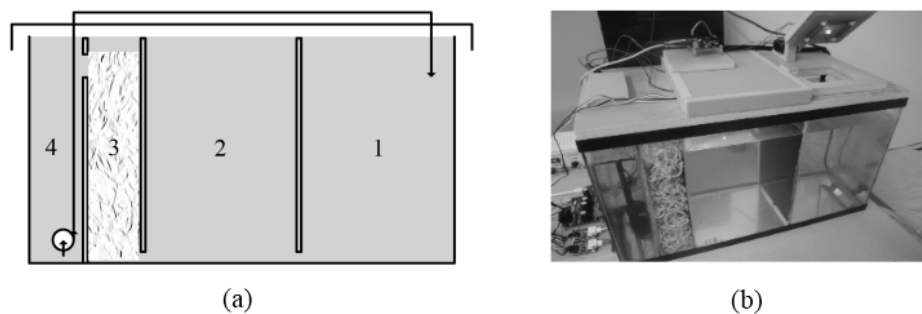


Figure 1. (a) Recirculation diagram of the habitat; (b) Physical realization of the habitat.

The first compartment has a motorized hatch and an aerator that allow for reconfigurability, making the system open (volatile) or closed (non-volatile) to the exchange of gases with the atmosphere. The second compartment includes a LED-based lamp that irradiates the plants and regulates their photosynthesis process. This compartment also gives access to a dosifier pump that increases the carbonate hardness (kH) of the water; the changes in kH are monitored through variations of the pH readings. The measurements from the sensors are processed by a computer/controller. The controller delivers the control signals that

regulate the LED-lamp power via a pulse-width modulation (PWM) board, and also controls the hatch, and the air and dosification pumps. The control signals can be generated by control laws or driven manually through a graphical user interface (GUI).

## D. Organization

The paper is organized as follows. Section II develops the mathematical model of a general reconfigurable aquatic habitat, while Section III specifies the design of the system used in this paper and the simulations performed. Section IV presents the results and provides remarks and discussions. Finally, Section V gives concluding remarks.

# II. A Model for a Reconfigurable Aquatic Habitat

The mathematical model developed for a reconfigurable aquatic habitat serves to determine the dynamic response of life-support critical variables. Focusing on respiration, the substances considered are dissolved oxygen (DO) and carbon dioxide (CO<sub>2</sub>). Carbonate hardness (kH) is also included because it affects the pH of the water, which is also a function of CO<sub>2</sub> concentrations. Consumption of kH is slow in well matured aquaria; it regulates the toxicity of ammonia, both of which are consumables for biofilters, and may be added to the water via a dosifier pump. Therefore, the life support critical variables for the model of this paper are DO, pH, and kH concentrations.

## A. Physico-Chemical Description

The mathematical model presented in this paper makes use of a control volume for each compartment. The model defines the interface for the mass balance equations that describe the relationship between the accumulation rate of a substance within each volume, measured in mass per units of time, and the difference between the incoming and outgoing mass flows. The assumptions made in the formulation of the general mathematical model are as follows: (a) recirculation flow is assumed laminar; (b) water density is constant; (c) the recirculation flow is the same for all compartments; (d) liquid solutions are perfectly well-mixed in all compartments; (e) output concentrations are those inside each compartment; (f) the water level of all compartments is the same and constant; (g) the volume of the compartments is constant.

### 1. Mass balance in a closed recirculating system

In liquid phase, masses are expressed in terms of concentrations, measured in milligrams per liter [mg/L] or parts per million [ppm] and the volume in which they are contained. Hence, for a substance  $x$  the mass balance equation is written as:

$$V[\dot{x}] = F_{in}[x]_{in} - F_{out}[x]_{out}$$

where  $V$  is the control volume defined for the mass balance,  $[x]$  is the concentration of the substance  $x$  inside the control volume,  $F_{in}$  and  $F_{out}$  are the incoming and outgoing flow rates, and  $[x]_{in}$  and  $[x]_{out}$  are the concentrations of those flows, respectively. The rate of change of the concentration  $[x]$  multiplied by the control volume  $V$  defines the rate of accumulation of  $x$  measured in [mg/h]. For a recirculating system, the incoming and outgoing flow rates are the same. This flow can also be variable and time-dependent, resulting in a non-linear system. For a recirculating system with  $n$  compartments and a variable flow  $F(t)$  the general mass balance can be expressed as:

$$A_i h \dot{[x]}_i = F(t) ([x]_j - [x]_i); \quad \forall \{1 \leq i \leq n\} \in \mathbb{N}; \quad j = \begin{cases} n & i = 1 \\ i - 1 & \forall i \neq 1 \end{cases} \quad (1)$$

where  $A_i$  are the surface areas of each compartment and  $h$  is the height of the water level for all compartments.

### 2. Diffusion at reduced recirculation flow rates

The system represented in Eq. 1 shows a reconfigurable recirculating system of  $n$  compartments, which may be sufficient if  $F > 0$ . However, diffusion becomes dominant when  $F \approx 0$  and an expression describing the

mass transfer produced by the gradient concentration between adjacent compartments becomes necessary. Using Fick's law of diffusion,<sup>10</sup> the transfer between the two compartments is proportional to the concentration difference between them, the equivalent cross-sectional area  $A_s$  of the flow through the separators, and a constant  $D$  that scales the rate of diffusion. Defining indexes:

$$k = \begin{cases} i+1 & i \neq n \\ i & i = n \end{cases} ; \quad l = \begin{cases} i & i = 1 \\ i-1 & i \neq 1 \end{cases}$$

and assuming for convention that  $[x]_l \leq [x]_i \leq [x]_k$ , the complete general equation for a closed recirculating system of  $n$  compartments is:

$$A_i h \dot{[x]}_i = f_{r,i} \equiv F(t) ([x]_j - [x]_i) + DA_{s_{k,i}} ([x]_k - [x]_i) + DA_{s_{i,l}} ([x]_i - [x]_l) \quad (2)$$

Parameters  $A_{s_{k,i}}$  and  $A_{s_{i,j}}$  represent the equivalent cross sectional areas of the flow between the compartment  $i$  and the adjacent compartments  $k$  and  $l$ , respectively. Note that, with the definitions of  $k$  and  $l$ , one of the diffusion terms is zero for the first and last compartments given that they only have one adjacent compartment. This paper uses an on/off switched signal for  $F(t)$  to facilitate the identification of the system parameters. As a consequence, it becomes a switched linear system as will be shown in Section III.

### 3. Reconfiguration into an open "volatile" system

Eq. 2 describes the dynamics of a closed recirculating system. It can be reconfigured into an open system by allowing the transfer of gases between the water and the atmosphere, making it *volatile*. The expression used to model the mass transfer (i.e. oxygen and carbon dioxide) between the water and the atmosphere is based on Henry's law of gas solubility and Fick's first law of diffusion.<sup>10,11</sup> The transfer is proportional to the contact surface area  $A_i$  between the gas and liquid phases, the concentration difference between the liquid phase  $[x]_i$  and the equivalent concentration of the gas phase  $[x]_{atm}$ , and a constant  $k_v$ . The equivalent concentration of the gas phase is given by the saturation level of the dissolved gas in the water. For example, for air at 15 °C the solubility saturation values for oxygen, carbon dioxide, and nitrogen are 10.08 [mg/l], 0.69 [mg/l], and 16.36 [mg/l], respectively.<sup>12</sup> Hence, the general equation for an open and volatile recirculating system is:

$$A_i h \dot{[x]}_i = f_{r,i} + k_{v,i} A_i ([x]_{atm} - [x]_i) \quad (3)$$

Given Eqs. 2 and 3, the complete reconfigurable recirculating system for  $n$  compartments is expressed as the switched system in Eq. 4.

$$\dot{[x]}_i = \frac{1}{h} \left( \frac{f_{r,i}}{A_i} + k_{v,i} ([x]_{atm} - [x]_i) u_\sigma \right); \quad \forall \{1 \leq i \leq n\} \in \mathbb{N}; \quad u_\sigma = \begin{cases} 0 & \text{non-volatile} \\ 1 & \text{volatile} \end{cases} \quad (4)$$

where  $u_\sigma$  is a switching signal that activates only one of the configurations at a time.

## B. Biological Processes

Biological processes affect the system in Eq. 4 by adding a term  $x_i$  to  $f_{r,i}$  to account for the rate of production or consumption of the substance  $x$  in the compartment  $i$  in [mg/h]. These rates may not describe biological processes directly, but may instead represent a measure of how chemical substances are produced or consumed in a given compartment, and may be used to incorporate ecophysiological models and constraints. This term may be used to describe how a physical condition (i.e. illumination) may influence a biological process contained therein. For example, assuming that the production of dissolved oxygen via photosynthesis is proportional by a constant  $k_{p,i}$  to the light intensity of a lamp driven by a voltage  $v_i(t)$ , then  $x_i = DO_i = k_{p,i} \cdot v_i(t)$ . In a similar fashion, other biological processes taking place in other compartments may be modeled by describing their rates of production or consumption,  $x_i$ , which may be influenced by environmental phenomena and constrained by their physiology. As a consequence, Eq. 4 is modified as shown in Eq. 5 to provide a mathematical description of a reconfigurable recirculating system of  $n$  compartments that incorporates rates of production and consumption of substances in each one of them. For this paper, rates of production and consumption are constant for consumers and switching for producers.

$$\dot{[x]}_i = \frac{1}{h} \left( \frac{1}{A_i} (f_{r,i} + x_i) + k_{v,i} ([x]_{atm} - [x]_i) u_\sigma \right) \quad (5)$$

### III. Design and Simulations of a Habitat

#### A. Design of a Four Compartment, Switching System

The simulations presented in this paper are prepared for a 10-gallon tank with  $n = 4$ . Its reconfigurability is made possible by an aerator in the first compartment:  $k_{v,1} = k_v \neq 0$ ;  $k_{v,2} = k_{v,3} = k_{v,4} = 0$ . The system has  $n - 1$  separators with cross sectional areas  $A_{s_a}$  for the first two, and  $A_{s_b}$  for the third. The model of the habitat is described by the switching system in Eq. 6. It considers that consumers are contained in the first compartment, producers in the second and a biofilter in the third. The fourth compartments is left for sensors and water pumps.

$$\frac{d}{dt} \vec{x} = \begin{cases} [A]_{cr} \vec{x} + [B] \vec{x} & \text{non-volatile; recirculating} \\ [A]_{cd} \vec{x} + [B] \vec{x} & \text{non-volatile; diffusive} \\ [A]_{or} \vec{x} + [B] \vec{x} + \vec{r}_g & \text{volatile; recirculating} \\ [A]_{od} \vec{x} + [B] \vec{x} + \vec{r}_g & \text{volatile; diffusive} \end{cases} \quad (6)$$

Matrices and vectors for Eq. 6 are:

$$[A]_{cr} = \begin{bmatrix} -\frac{F}{A_1 h} & 0 & 0 & \frac{F}{A_1 h} \\ \frac{F}{A_2 h} & -\frac{F}{A_2 h} & 0 & 0 \\ 0 & \frac{F}{A_3 h} & -\frac{F}{A_3 h} & 0 \\ 0 & 0 & \frac{F}{A_4 h} & -\frac{F}{A_4 h} \end{bmatrix}; \quad [A]_{cd} = \begin{bmatrix} -\frac{DA_{s_a}}{A_1 h} & \frac{DA_{s_a}}{A_1 h} & 0 & 0 \\ -\frac{DA_{s_a}}{A_2 h} & 0 & \frac{DA_{s_a}}{A_2 h} & 0 \\ 0 & -\frac{DA_{s_a}}{A_3 h} & -\frac{D}{A_3 h} (A_{s_a} - A_{s_b}) & \frac{DA_{s_b}}{A_3 h} \\ 0 & 0 & -\frac{DA_{s_b}}{A_4 h} & \frac{DA_{s_b}}{A_4 h} \end{bmatrix}$$

$$[A]_{or} = \begin{bmatrix} -\frac{1}{h} \left( \frac{F}{A_1} + k_v \right) & 0 & 0 & \frac{F}{A_1 h} \\ \frac{F}{A_2 h} & -\frac{F}{A_2 h} & 0 & 0 \\ 0 & \frac{F}{A_3 h} & -\frac{F}{A_3 h} & 0 \\ 0 & 0 & \frac{F}{A_4 h} & -\frac{F}{A_4 h} \end{bmatrix}; \quad \vec{x} = \begin{bmatrix} [x]_1 \\ [x]_2 \\ [x]_3 \\ [x]_4 \end{bmatrix}; \quad \vec{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}; \quad \vec{r}_g = \begin{bmatrix} \frac{k_v [x]_g}{h} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$[A]_{od} = \begin{bmatrix} -\frac{1}{h} \left( \frac{DA_{s_a}}{A_1} + k_v \right) & \frac{DA_{s_a}}{A_1 h} & 0 & 0 \\ -\frac{DA_{s_a}}{A_2 h} & 0 & \frac{DA_{s_a}}{A_2 h} & 0 \\ 0 & -\frac{DA_{s_a}}{A_3 h} & -\frac{D}{A_3 h} (A_{s_a} - A_{s_b}) & \frac{DA_{s_b}}{A_3 h} \\ 0 & 0 & -\frac{DA_{s_b}}{A_4 h} & \frac{DA_{s_b}}{A_4 h} \end{bmatrix}; \quad [B] = \begin{bmatrix} \frac{1}{A_1 h} & 0 & 0 & 0 \\ 0 & \frac{1}{A_2 h} & 0 & 0 \\ 0 & 0 & \frac{1}{A_3 h} & 0 \\ 0 & 0 & 0 & \frac{1}{A_4 h} \end{bmatrix}$$

The substances  $x$  considered are dissolved oxygen (DO), carbon dioxide (CD) and carbonate hardness (kH). The output equation is  $y = [[DO]_4 \text{ pH}_4 [kH]_4]^T$ , where the conversion from  $[CD]_4$  into pH is given by<sup>12</sup>  $\text{pH}_4 = 6.3 - \log([CD]_4/[kH]_4)$ . This transformation is valid within a 5-10% accuracy for  $6.5 \leq \text{pH} \leq 9.5$ . The vector  $\vec{r}_g$  establishes the equivalent concentration of gases in the atmosphere (an infinite buffer) as a reference value for the volatile configuration of the system. The model is implemented making use of the parameters listed in Table 1 and the production and consumption rates are presented in Table 2.

#### B. Simulations Performed on the Model

The simulations of this model are performed in MATLAB Simulink. They are implemented with a stiff Mod. Rosenbrock numeric method with maximum step of 0.01. The first simulation implements a closed-loop on/off control of the DO concentration via photoregulation (by photosynthesis). This experiment intends to reproduce results comparable to those reported with the CEBAS minimodule.<sup>5</sup> In this case, a simple controller turns on and off the lamp of the second compartment when the DO concentration in the fourth reaches 4.0 [mg/l] and 6.5 [mg/l], respectively. The simulation time is 21 days and its initial conditions are in equilibrium with the equivalent concentration of the atmosphere at 22 °C at sea level. A second simulation implements an illumination duty cycle similar to the first experiment, i.e. with a period of 6 hours. In addition, a small disequilibrium is added by changing the rates of consumption in the biofilter to  $DO_3 = -6.0$  [mg/h] and  $CD_3 = 6.0$  [mg/h], to simulate a mortality and its decomposition in the system.

**Table 1. Model parameters used in the simulation of the four compartment reconfigurable aquatic habitat.**

Parameter	Value	Units	Description
$h$	26.28	cm	Height of the water level in the habitat
$A_1 = A_2$	533.40	cm <sup>2</sup>	Top surface area of the first and second compartments
$A_3 = A_4$	186.69	cm <sup>2</sup>	Top surface area of the third and fourth compartments
$A_{s_a}$	12.60	cm <sup>2</sup>	Cross-section area of the opening in the separators type “a”
$A_{s_b}$	48.00	cm <sup>2</sup>	Cross-section area of the opening in the separators type “b”
$F$	390	l/h	Flow rate of the recirculation pump
$[DO]_g$	8.40	mg/l	Dissolved oxygen saturation concentration
$[CD]_g$	0.69	mg/l	Dissolved carbon dioxide saturation concentration
$D$	1500	cm/h	Liquid phase diffusion constant
$k_v$	200	cm/h	Gas transfer diffusion constant, for DO and CD only

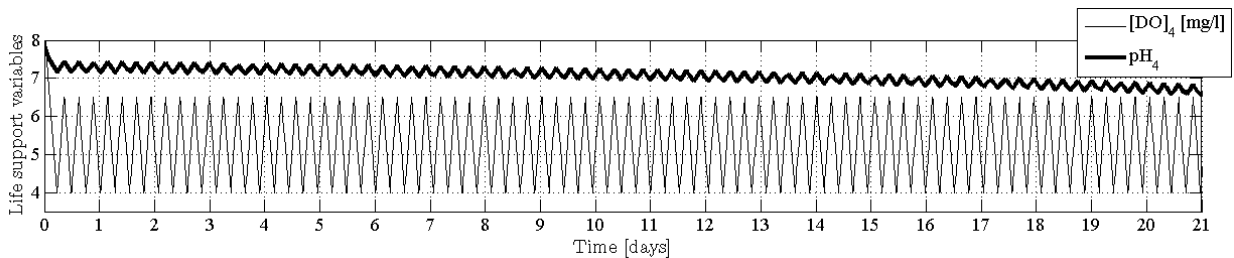
**Table 2. Production and consumption rates for  $\bar{x}$  in [mg/h]**

	$DO_1$	$CD_1$	$DO_2$	$CD_2$	$DO_3$	$CD_3$	$kH_3$
Values	-40.0	40.0	90.0	-90.0	-5.0	5.0	-3.5

The simulation time is also 21 days. A third test simulates the failure and replacement of the water pump. The pump fails at 48 hours into the simulation and is fixed within 6 hours after 24 hours from the fault. The system returns to regular operation at 76 hours. In this experiment two cases are considered: (a) the oxygen levels are regulated via photoregulation (b) the system is switched to a volatile configuration during the fault until it resumes normal operation. Both cases consider measurements of DO concentration in the first and fourth compartments.

## IV. Results and Discussion

Figures 2 through 5 show the results of the simulations described above. Figure 2 presents the on/off control of the DO level for a balanced system, varying between 4 [mg/l] and 6.5 [mg/l] in the fourth compartment; the consumption and production rates of the compartment containing plants is turned on and off depending on these limit values, respectively. The result is similar to results reported in the past,<sup>5</sup> which also show the progressive deterioration of the pH level, most probably due to consumption of equivalent carbonate hardness (kH) in the biofilter. The rates of consumption and production used (Table 2) result in a lightning duty cycle of  $\sim 6$  hours. Such on/off control does not account for the physiological requirements of the biological elements. Therefore, other control strategies<sup>13</sup> need to be developed to operate bioregenerative life support systems. Given the results obtained for a 10-gallon (37.85 [l]) tank, estimations can be made for experiments performed with the CEBAS-minimodule: with a volume  $\sim 8.8$  [l], and assuming that the



**Figure 2. Dissolved oxygen and pH for conditions comparable to CEBAS experiments.<sup>5</sup>**

system was perfectly balanced, the biological oxygen demand (BOD) should have been nearly half of the oxygen generation rate, or  $\sim 1.2$  [mg/h/l]. Hence, its oxygen production rate results in  $\sim 2.4$  [mg/h/l]. Values reported<sup>5</sup> show that the system was apparently producing somewhere between “3.5 and 7.5 mg/l” per hour, which is a comparable value. The authors<sup>5</sup> also report about the “steepness” of the oxygen production, which in this paper is obtained by taking the first derivative of the DO concentration of the fourth compartment – see Fig. 3. It shows that the maximum steepness achieved is 1.0 [mg/l/h] with stabilization values of 0.8 [mg/l/h]. These values are comparable to the results obtained with CEBAS,<sup>5</sup> which show a “steepness” also centered in zero and taking values between  $\pm 1$  [mg/l/h]. Despite differences in volume, this simplified model is able to reproduce values similar to CEBAS, which at the same time serve to validate the quantities and parameters used therein, and provides a tool to perform forensic analysis to some extent.

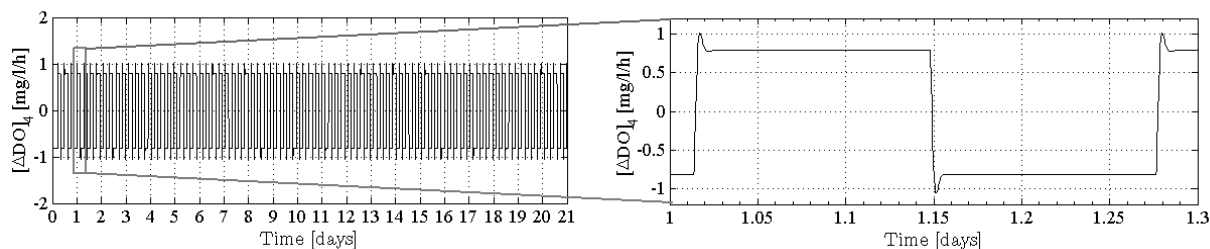


Figure 3. Observation on steepness of oxygen production.

The result of the second simulation is reported in Fig. 4. It shows the difference of using an open-loop versus closed-loop control; a small unbalance of just 1 [mg/h] results in a progressive deterioration of dissolved oxygen levels in an open-loop duty-cycle, which potentially would harm the consumers contained therein. In contrast, the use of feedback and a regulation mechanism as simple as an on/off control is sufficient to balance the system. These observations highlight the importance of feedback control mechanisms to bring a simple closed environmental system to balance, and (2) may help understand and raise questions about the effects of unattended unbalances in larger-scale environmental systems like the Earth, for which climate change increasingly becomes a concern. Furthermore, other questions and experiments<sup>13</sup> may contribute to better understand the reach and limitations of the so-called Gaia hypothesis, which states that biological processes alone and their interaction will compensate for environmental unbalances in Earth’s biosphere.<sup>1</sup>

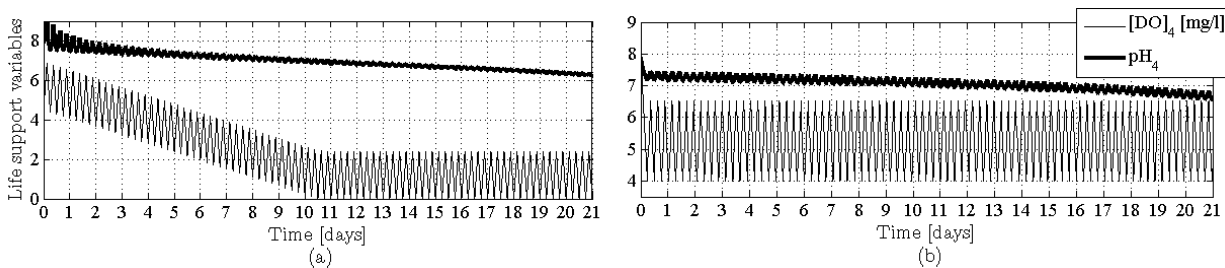


Figure 4. Response of an unbalanced system driven by (a) a fixed open-loop duty cycle, and (b) an on/off closed loop control.

Finally, Fig. 5 presents the simulation of the failure and replacement of the recirculation water pump. The time responses presented in this case show two different approaches to handle the contingency. Fig. 5 (a) allows the system to automatically regulate the oxygen concentration via photosynthesis and diffusion, and shows the dissolved oxygen concentrations for compartments 1 and 4. If the consumer species contained in the first compartment are not able to withstand concentration levels below 2 [mg/l], then this approach may not be the preferred one. Instead, a different “fail-safe” mechanism may be necessary, e.g. an aerator, which in Fig. 5 (b) becomes more appropriate to guarantee acceptable levels of dissolved oxygen in the system. This result also shows that experiments with small-scale reconfigurable environmental systems may serve not only test control laws, but also to combine them with other automated safety mechanisms that may prove critical during contingencies.

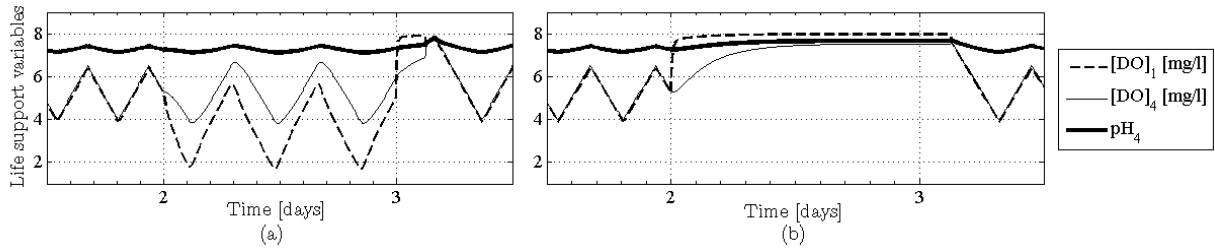


Figure 5. Result of two different “fail-safe” contingency policies upon a fault in the recirculation pump.

## V. Conclusions

This paper presented the modeling, design and simulation of a reconfigurable aquatic habitat intended for experiments in life support control research. The model focuses on the process of respiration and produces results comparable to those reported in ground-based and spaceflight experiments. The model is general enough to enable the design and simulation of other systems of the same nature. Results obtained and reported in this paper highlight the importance of feedback control in combination with fail-operational/fail-safe mechanisms to balance and support life in closed environmental systems. This paper supports the use of small-scale aquatic habitats to explore concepts that may be difficult to test in larger-scale systems. Future work will focus on (1) the validation of experiments, (2) the incorporation of ecophysiological phenomena in the mathematical model, (3) proposing feedback control methods<sup>13</sup> to balance these systems while considering physiological requirements, and (4) the development and proposal of system requirements for the design, integration and automation of larger scale Controlled Environmental Life Support Systems (CELSS).

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