

A FAM-based Switched Control Approach for the Automation of Bioregenerative Life Support Systems

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The automation of bioregenerative life support systems poses challenges for the development of model-based approaches given the varying characteristic of the biological processes that constitute them. Switching control paradigms offer an alternative for the management of such uncertainty by introducing flexibility into the control path and allowing for different control modes depending on the operational conditions of the system. This paper presents a perception-based switching control strategy that makes use of sensor information to define and act upon those conditions. Abundant sensor information gives rise to sensing spaces in which the operational conditions of the system are found. A decomposition of the sensing spaces into perceptual elements allows for automation and integration strategies, and for the implementation of fail-safe and fail-operational mechanisms. This paper proposes the use of agents based on fuzzy associative memories to decompose sensing spaces into granular structures composed of n -dimensional non-interactive fuzzy sets. The granular structures allow for the incremental development and automation of the system by associating a control task to each granule. The method presented in this paper is applied to the dynamic model of a reconfigurable aquatic habitat. The habitat serves as a small-scale bioregenerative test bed for life support control research. The method used in this paper may also enable cognitive resources to enhance human interaction with the system.

I. Introduction

The capability of habitation systems to regenerate life support consumables, such as oxygen, is one of the challenges of long duration human space flight.¹ Such capability would reduce the frequency of resupply missions and presumably also reduce their operation cost. One option for this challenge is the use of bioregenerative life support systems (BLSS), which make use of biological processes to transform biological by-products back into consumables. However, uncertainties from ecophysiological phenomena of biological processes create challenges for the control and automation of BLSS. Switching control paradigms²⁻⁵ offer an alternative for the management of such uncertainties by introducing flexibility into the control path and allowing for different control modes depending on the operational conditions of the system. This paper makes use of a perception-based approach to the switching control paradigm. The availability of abundant sensor information and the capability to define perceptual elements enables a modular approach to system automation and integration, and for the implementation of fail-safe and fail-operational mechanisms. This paper proposes the use of agents based on fuzzy associative memories (FAM's)⁶⁻⁸ to develop granular structures composed of n -dimensional non-interactive fuzzy sets for the switching mechanism. The granular structures also allow for an incremental development and automation by associating a control task to each granule. The objective of this paper is to implement the switched control strategy on the dynamic model of a reconfigurable aquatic habitat to introduce flexibility into the dynamics of the system and allow for different control modes depending on its operational condition. Although results presented are based on simulations, hardware of the system described is used to identify model parameters.

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A. Background

The work described here may be framed within the field known as *biospherics*,¹ which aims to: (1) build models of terrestrial ecosystems to better understand the processes that regulate life; (2) build habitats to extend the human presence to extreme environments on Earth and beyond; and (3) develop technologies that may help to utilize natural resources efficiently and in a more sustainable way. The project builds on the use of aquaria, or aquatic habitats, as small-scale platforms for Earth-based and spaceflight life support systems research and applications,⁹ in this case making use of aquatic habitats to: (1) study the balance of small-scale ecosystems that contain a combination of natural agents (botanical, animal) and artificial agents (controllers); (2) investigate the integration and automation of bioregenerative life support processes for artificial habitats; and (3) help develop technologies that may increase the sustainability of environmental and production systems on Earth. Therefore, the goal of the project is 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).

Past projects have made use of aquatic habitats for experiments in zoology and physiology in low Earth orbit (LEO),¹⁰⁻¹⁴ and for ecotoxicological studies in ground-based hardware.^{9,15} Such habitats have made use of on/off control (similar to thermostats) to regulate life support variables, and do not necessarily consider all the physiological requirements of their biological elements. Results obtained with the Closed Equilibrated Biological Aquatic System (CEBAS) minimodule in 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.¹¹ This module also flew in STS-107,¹³ but no results were reported due to the accident of the Space Shuttle Columbia. A recent initiative by the Japanese Aerospace Exploration Agency (JAXA) plans to include an aquatic habitat in their International Space Station module, Kibo.¹⁶ Beyond these efforts, very little has been done to make use of aquatic habitats for research in spaceflight life support control and automation.

B. Organization

The paper is organized as follows. Section II describes the mathematical model of the reconfigurable aquatic habitat, while Section III presents the FAM-based agent architecture for its automation, the implementation on the habitat, and the simulations performed. Section IV reports the results and provides remarks and discussions. Finally, Section V offers concluding remarks and suggests future directions.

II. The Reconfigurable Aquatic Habitat

A. Preliminary Description

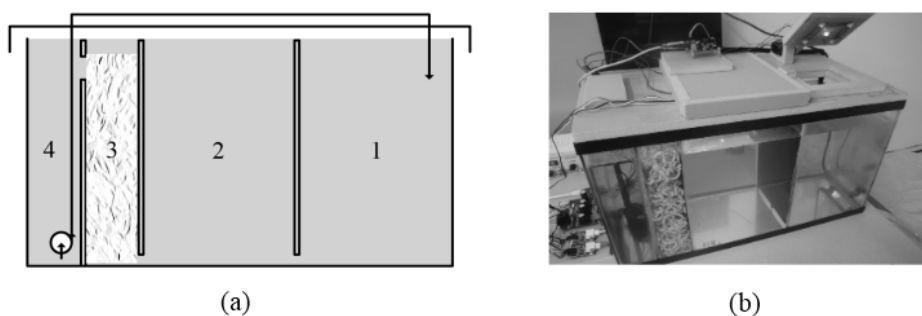


Figure 1. (a) Recirculation diagram of the habitat; (b) Physical realization of the habitat.

The model of the aquatic habitat¹⁷ looks at 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 photosynthesis, producing the oxygen needed by consumers and aiming to maintain acceptable concentration levels in the habitat. Water serves as the medium in which these quantities are stored (dissolved), and through which they are exchanged between the organisms. The habitat consists of a 10-gallon tank divided in four compartments by three separators, as shown in Fig. 1; 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. 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; this mechanism is triggered as a fail-safe mechanism when the DO levels reach a minimum of 2.0 [mg/l]. 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 dosifier pumps. The control signals can be generated by control laws or driven manually through a graphical user interface (GUI).

B. Model of the Reconfigurable Aquatic Habitat

The model of the habitat is described by¹⁷ the switching system in Eq. 1, where x are substances, such as dissolved oxygen or carbon dioxide, and $[x]$ their concentration in [mg/l]. The system has three separators with cross sectional areas A_{s_a} for the first two, and A_{s_b} for the third. The assumptions 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.

$$\frac{d}{dt}[\vec{x}] = \begin{cases} [A]_{cr}[\vec{x}] + [B]\vec{x} & \text{non-volatile; recirculating} \\ [A]_{cd}[\vec{x}] + [B]\vec{x} & \text{non-volatile; diffusive} \\ [A]_{or}[\vec{x}] + [B]\vec{x} + \vec{r}_g & \text{volatile; recirculating} \\ [A]_{od}[\vec{x}] + [B]\vec{x} + \vec{r}_g & \text{volatile; diffusive} \end{cases} \quad (1)$$

Matrices and vectors for Eq. 1 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 by¹⁸ $\text{pH}_4 = 6.3 - \log([CD]_4/[kH]_4)$. 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.

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 ²	Top surface area of the first and second compartments
$A_3 = A_4$	186.69	cm ²	Top surface area of the third and fourth compartments
A_{s_a}	12.60	cm ²	Cross-section area of the opening in the separators type “a”
A_{s_b}	48.00	cm ²	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	94.0	-94.0	-7.0	7.0	-3.5

III. A Switched Control Approach for the Aquatic Habitat

This section develops the switching-controller used for the aquatic habitat. It makes use of FAM’s to define operating conditions and the switching attributes of the controller. The controller is encapsulated within an architecture known as a FAM-based agent.^{6,7} A description of the agent is presented in Subsection A and its application to the control of the habitat is presented in Subsection B. Note that the notation used to describe the agent architecture is not related to that of Section II.

A. The FAM-Based Agent Architecture

The FAM-based agent represents a switching control approach, in which controllers are assigned in a modular fashion to each condition of the system in the form of (Situation, Controller).⁷ It introduces flexibility to the automation of the system and enables its incremental development. The architecture is characterized by (1) a perception function that results in a granular structure, (2) a set of controllers, and (3) a correspondence function that associates a controller to each situation and combines all possible control actions into an integrated control signal.

1. The perception function and granular structure

Given n measurable variables x_i for $i = 1, 2, \dots, n$ and their universes of discourse X_i so that $x_i \in X_i \subseteq \mathfrak{R}$, and assuming the universes are non-redundant and non-interactive:

$$X_i \neq X_j \quad \forall \begin{cases} i = 1, 2, \dots, n \\ j = 1, 2, \dots, n \\ i \neq j \end{cases}$$

Each universe X_i is partitioned in k_i subsets, each of which is denoted as $X_i^\alpha \subset X_i$, $\alpha = 1, 2, \dots, k_i$. The subsets are described by continuous membership functions $\mu_{X_i^\alpha}(x_i)$, which are normal and convex.¹⁹ In addition, the partitions of the universes of discourse X_i^α satisfy the Ruspini condition:²⁰

$$\sum_{\alpha=1}^{k_i} \mu_{X_i^\alpha}(x_i) = 1 \quad \forall i = 1, 2, \dots, n \quad (2)$$

A number of l situations or conditions under which the system may operate are possible; they are described by non-interactive fuzzy sets \tilde{A}_j , for $j = 1, 2, \dots, l$. The l fuzzy conditions, or situations, are the Cartesian product of the combination of the subsets X_i^α in X_i . The Cartesian product is implemented with the *minimum* operator as in Eq. 3, for the l number of possible situations or conditions defined in Eq. 4.

$$\tilde{A}_j(x_1, \dots, x_n) = \min_{\substack{i=1, \dots, n \\ \alpha=1, 2, \dots, k_i}} (\mu_{X_i^\alpha}(x_i)); \quad \forall j = 1, 2, \dots, l \quad (3)$$

$$l = \prod_{i=1}^n k_i = k_1 \cdot k_2 \cdot \dots \cdot k_n \quad (4)$$

The set $\tilde{A} = \{\tilde{A}_j\}$, for $j = 1, 2, \dots, l$ forms a granular structure in which each granule \tilde{A}_j potentially represents a different operating condition of the system and a percept of the FAM-based agent.

2. The control actions

Similarly, a set of up to l different control laws make up the set of control signals $U = \{u_j\}$. Feedback control laws generate control signals u_j in direct correspondence with each condition \tilde{A}_j and to form the set $U = \{u_1, u_2, \dots, u_l\}$. The maximum number of different control signals is limited by l . The control signals can be obtained using model-based methods of modern control theory or techniques such as fuzzy logic, neural-networks, genetic algorithms or a combination of them. Error modulation⁶ or a similar technique is required for controllers that make use of integral control actions.

3. Correspondence function and the integrated control signal

Given the sets \tilde{A} and U , the Correspondence Function Ω is defined in pairs as in Eq. 5.

$$\begin{aligned} \Omega : \tilde{A} &\rightarrow U \\ \Omega = \{\Omega_j\} &= \left\{ \left(\tilde{A}_j(x_1, \dots, x_n), u_j(t) \right) \right\} \end{aligned} \quad (5)$$

The pairs in Ω indicate the relationship between the fuzzy conditions and the control signals. The FAM is defuzzified with the weighted average technique and an integrated control signal is obtained. The weights are the membership values of every fuzzy condition, and the weighted arguments are the associated control signals. The expression for the defuzzification and the integrated control signal is:

$$u_I(x_1, \dots, x_n, t) = \frac{\sum_{i=1}^l \mu_{\tilde{A}_i}(x_1, \dots, x_n) \cdot u_i(t)}{\sum_{i=1}^l \mu_{\tilde{A}_i}(x_1, \dots, x_n)} \quad (6)$$

B. Application to the Model of the Habitat

This Subsection presents the application of the FAM-based agent architecture to the control of the DO levels in the model of the aquatic habitat presented in Section II. It defines (1) the operating range of the life support variables considered, which are the DO and pH in the fourth compartment; (2) the operational conditions that result from the operating ranges and the controllers used to change the power level of the photosynthetic lamp that produces oxygen in the second compartment; and (3) the simulation performed on the habitat for this paper.

1. Life support signals and their operating ranges

The life support variables considered are the DO and pH in the fourth compartment. Their operating ranges and fuzzy values are defined in Fig. 2. There are two conditions for the DO concentrations: nominal and low. The pH instead has three ranges: nominal, high and low. These ranges are defined according to conservative measures of the minimum DO concentration recommended for fresh water animals (2 [mg/l]), and the pH ranges in which most aquatic animals can live with minimum stress.¹⁸

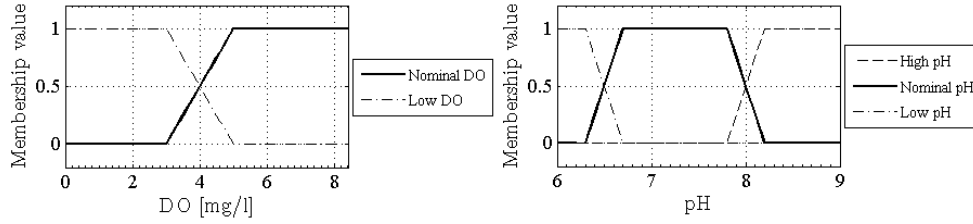


Figure 2. Fuzzy partitions of the DO and pH variables.

2. Control laws and their operating conditions

Two types of control actions are used in this paper to manipulate the power level of the photosynthetic lamp: (1) power on and constant and (2) a proportional-integral (PI) controller. The PI controller, $u(t) = (P + I/s)e(t)$, is used in most of the operating conditions, with $P = 200$ and $I = 50$. The changes found in the PI controller between different operating conditions are in the feedback signal used and its reference. From Subsection A, the operational conditions result from the combination of the operating ranges of the variables considered, in this case DO and pH in the fourth compartment. Table 3 shows a representation of the combination of these conditions and the control actions used in each case. Note that because the controller used includes an integral component (i.e. a proportional-integral controller), the use of the error modulation technique⁶ is required. The reference signal used for the nominal and DO_{min} controllers has a duty cycle of 18 by 6 hours to account for the physiological requirements of the botanical elements. The nominal condition sets its reference in 6.0 [mg/l] for 18 hours and at 5.0 [mg/l] during the other six. Similarly, the reference signal for the DO_{min} controller follows the same duty cycle for 4.5 [mg/l] and 4.0 [mg/l].

Table 3. Control actions for different operating conditions.

	Low pH	Nominal pH	High pH
Nominal DO	$pH_{ref} = 6.3$	Nominal	$pH_{ref} = 8.0$
Low DO	Lamp on	$DO_{ref} = 3$	DO_{min}

3. Simulation performed on the habitat model

The simulation explores the operational condition transitions triggered in the system by the depletion of the supply of kH solution to the second compartment. This substance is consumed by the biofilter in the process of nitrification. The source of kH is inhibited until day 14 in the simulation, in which it is restored. This simulation automates the operation of the system with the FAM-based agent approach. Its purpose is to show the switching attributes of the FAM-based agent and a photoregulation strategy based on continuous feedback control, while considering the physiological requirements of its biological elements. The simulations are implemented with a stiff Mod. Rosenbrock numeric method with maximum step of 0.01. Initial conditions are $[DO] = 8.4$ [mg/l], $[CD]=0.69$ [mg/l], and $[kH]=20$ [mg/l]. 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.

IV. Results and Discussion

The depletion of the kH in the system deteriorates the pH below nominal values as shown during day 9 and just before day 10. Between days 9 and 14 the system transitions into different operational modes and recovers its nominal condition thereafter. Figs. 3, 4 and 5 show the dynamics of these transitions from three perspectives. Fig. 3 looks at the evolution of life support variables, DO and pH; Fig. 4 presents the behavior of the lamp; and Fig. 5 shows the membership value of the operational conditions over time. The system remains fail-op/fail-safe within the conditions defined in Table 3 and without triggering the aerator (another fail-safe mechanism). Between day 9 and 10 the system tries to keep a minimum level of DO while regulating the pH of the system around 6.3. When the oxygen level raises above 6.0 [mg/l] on day 12, the

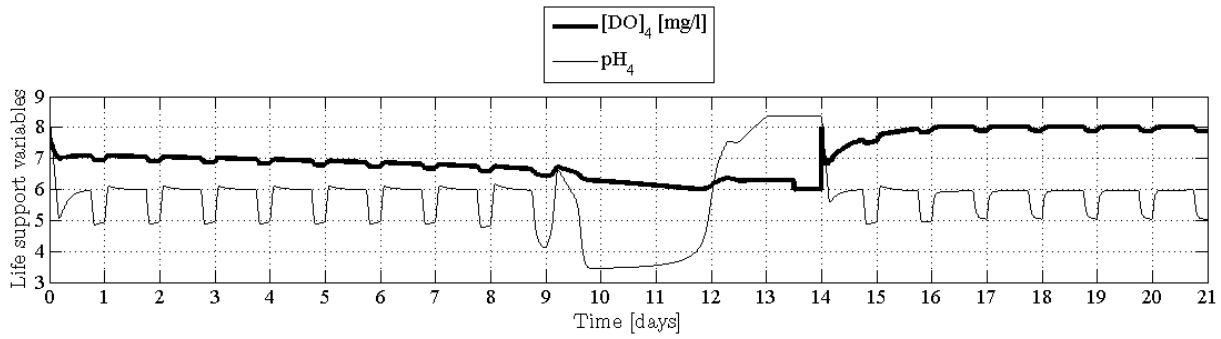


Figure 3. Evolution of the life support variables during the simulation

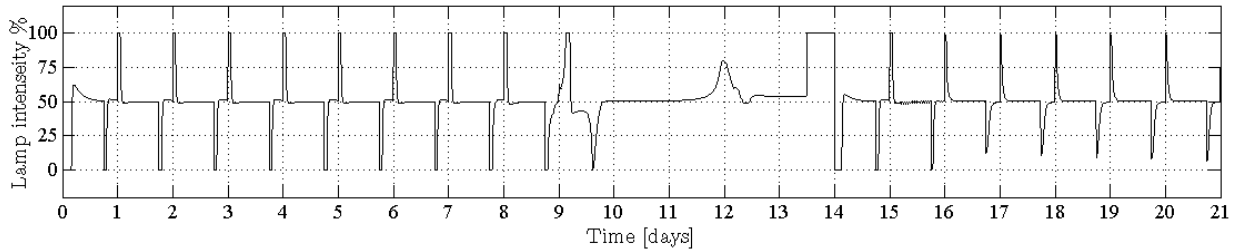


Figure 4. Lamp intensity percentage in response to controllers enabled during the simulation

agent is dedicated to change the lamp intensity to achieve pH 6.3, as can be observed in Fig. 3 between days 12 and ~13.5. Observe the good standing of the oxygen level during this period and the recovery of the nominal condition after day 14 in Fig. 5. It is important to note that the lamp intensity shows the behavior of the agent or controller switching between operational conditions. Note in Fig. 4 the smoothness of the lamp behavior up to day 13.5 in correspondence to the membership values shown in Fig. 5. At day 12 occurs a transition that shifts from a dominant low-DO/low-pH condition to a nominal-DO/low-pH condition. Just before and after day 12, Fig. 4 shows a smooth increase and decrease in the lamp intensity percentage for this transition. Note that although it is not possible to precisely determine what the system is doing from Figs. 3 and 4, Fig. 5 allows the identification of the operational conditions of the system with the evolution of their membership values over time. This information is used in this paper as a switching mechanism only, but it may well also be used to develop data-abstraction algorithms, using e.g. fuzzy logic or neural networks, to make the system observable to human operators from the perspective of cognitive engineering. This opens up opportunities for supervisory control in the sense of Sheridan,²¹ adjustable autonomy and human-centered design. This is especially of interest for operations in mission control and support centers, which require resources to build up situational awareness and tools for real-time decision making.

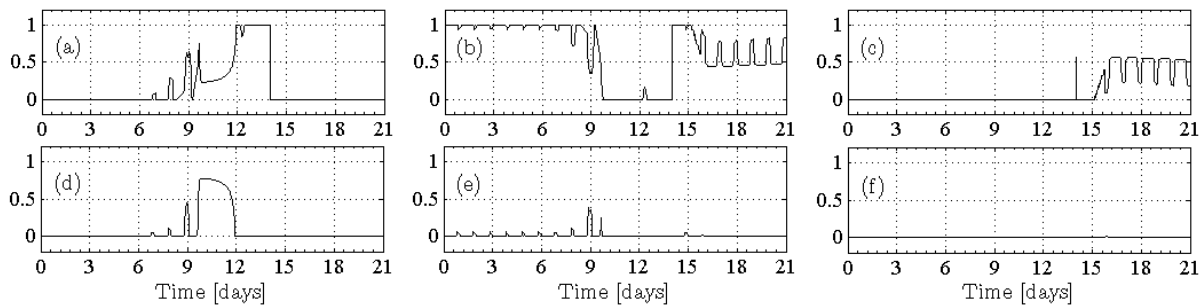


Figure 5. Membership values of the conditions defined in Table 3: (a) nominal-DO/low-pH; (b) all nominal; (c) Nominal-DO/High-pH; (d) low-DO/low-pH; (e) low-DO/nominal-pH; (f) Low DO - High pH.

V. Conclusions

This paper presented a switched control approach to the automation of a BLSS for aquatic organisms. It presented the dynamic model of a reconfigurable aquatic habitat and the framework of the FAM-based agents as the tool to implement a switched control paradigm. Such approach offers an alternative for the management of uncertainties introduced by ecophysiological phenomena present in BLSS by adding flexibility to the control path and allowing for different control modes depending on operational condition of the system. This paper implements the FAM-based agent as a perception-based switching control strategy that makes use of sensor information to define and act upon those conditions. The information generated by the perceptual elements, or granules, is used to switch between various control actions, and thus to regulate the behavior of the system. This information may also be used for purposes beyond the switching mechanism. Future work aims to propose methods to manage increasingly complex granular structures needed for larger habitats and the validation of experiments. It will also look at using perceptual information as a resource for (1) situational awareness to make these systems more observable, (2) adjustable autonomy mechanisms to enhance human-system interaction, and (3) additional fail-safe/fail-operational mechanisms.

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References

- ¹Eckart, P., *Spaceflight Life Support and Biospherics*, Microcosm Press and Kluwer Academic Publishers, USA, 1996.
- ²Vu, L. and Liberzon, D., "Supervisory Control of Uncertain Linear Time-Varying Systems," *Automatic Control, IEEE Transactions on*, Vol. 56, No. 1, 2011, pp. 27–42.
- ³Lin, H. and Antsaklis, P., "Stability and Stabilizability of Switched Linear Systems: A Survey of Recent Results," *Automatic Control, IEEE Transactions on*, Vol. 54, No. 2, 2009, pp. 308–322.
- ⁴Liberzon, D., *Switching in Systems and Control*, Birkhäuser, 2003.
- ⁵Hespanha, J. P., Liberzon, D., and Morse, A. S., "Overcoming the limitations of adaptive control by means of logic-based switching," *Systems & Control Letters*, Vol. 49, No. 1, 2003, pp. 49–65, Adaptive Control.
- ⁶Drayer, G. and Strefezza, M., "Integral Control with Error Modulation in a FAM-based Agent for a Furuta Inverted Pendulum," *2008 IEEE World Congress on Computational Intelligence*, Hong Kong, June 01-06 2008, pp. 1590–1597.
- ⁷Drayer, G. and Strefezza, M., "A FAM-based Agent for a Ball and Beam," *IEEE-SOFA 2007. 2nd IEEE International Workshop on Soft Computing Applications*, Gyula, Hungary, and Oradea, Romania, August 21-23 2007, pp. 89–94.
- ⁸Ross, T., *Fuzzy Logic with Engineering Applications*, John Wiley & Sons, 2nd ed., 2004.
- ⁹Slenzka, K., Dünne, M., and Jastorff, B., "Biomonitoring and risk assessment on earth and during exploratory missions using AquaHab," *Advances in Space Research*, Vol. 42, No. 12, 2008, pp. 1944–1950.
- ¹⁰Blüm, V. and Paris, F., "Possible applications of aquatic bioregenerative life support modules for food production in a Martian base," *Advances in Space Research*, Vol. 31, No. 1, 2003, pp. 77–86.
- ¹¹Blüm, V. and Paris, F., "Novel aquatic modules for bioregenerative life-support systems based on the closed equilibrated biological aquatic system (CEBAS)," *Acta Astronautica*, Vol. 50, No. 12, 2002, pp. 775–785.
- ¹²Blüm, V., Andriske, M., Ludwig, C., Paassen, U., and Voeste, D., "The CEBAS mini-module: A self-sustaining closed aquatic ecosystem for spaceflight experimentation," *Advances in Space Research*, Vol. 31, No. 1, 2003, pp. 201–210.
- ¹³Blüm, V., "Aquatic modules for bioregenerative life support systems: Developmental aspects based on the space flight results of the CEBAS mini-module," *Advances in Space Research*, Vol. 31, No. 7, 2003, pp. 1683–1691.
- ¹⁴Blüm, V., "Aquatic Modules for Bioregenerative Life Support Systems: Developmental Aspects based on the Space Flight Results of the C.E.B.A.S. Mini-Module," *Advances in Space Research*, Vol. 31, 2003, pp. 1683–1691.
- ¹⁵Stan, I. A., *Bioavailability and biological properties of several selected ionic liquids*, Ph.D. thesis, Fachbereich Biologie/Chemie, Universität Bremen, September 2009.
- ¹⁶Watanabe-Asaka, T., Mukai, C., and Mitani, H., "Technologies and Analyses Using Medaka to Evaluate Effects of Space on Health," *Biological Sciences in Space*, Vol. 24, 2010, pp. 3–9.
- ¹⁷Drayer, G. and Howard, A., "Design, Modeling and Simulation of a Reconfigurable Aquatic Habitat for Life Support Control Research," *41st International Conference on Environmental Systems*, AIAA, Portland, Oregon, July 2011.
- ¹⁸Timmons, M. and Ebeling, J., *Recirculating Aquaculture*, North Eastern Regional Aquaculture Center, 2007.
- ¹⁹Zadeh, L., "Fuzzy sets," *Information and Control*, Vol. 8, No. 3, 1965, pp. 338–353.
- ²⁰Ruspini, E. H., "A new approach to clustering," *Information and Control*, Vol. 15, No. 1, 1969, pp. 22–32.
- ²¹Sheridan, T. B., *Humans and Automation: System Design and Research Issues*, John Wiley & Sons, Inc., New York, NY, USA, 2002.