

A Granular Approach to the Automation of Bioregenerative Life Support Systems that Enhances Situation Awareness

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Abstract—Bioregenerative life support systems introduce novel challenges for the development of model-based approaches to their control given the varying characteristic of the biological processes that constitute them. Switching control paradigms provide an alternative to manage such uncertainty by allowing flexibility into the control path, enabling different control modes depending on the situation of the system. This paper presents a perception-based approach that combines sensor information to define those conditions and act upon them. Combined sensor information creates sensing spaces in which the operational conditions of the system are found. The decomposition of the sensing spaces into perceptual elements or granules allows for situation assessment, system integration strategies, and the implementation of fail-safe and fail-operational mechanisms - all these critical in a wider range of complex socio-technical systems. This paper proposes the use of intelligent agents based on fuzzy associative memories (FAM's) to decompose sensing spaces into granular structures composed of n -dimensional non-interactive fuzzy sets. Granular structures resulting from such decomposition allow for the incremental development and automation of the system by associating a control task to each operational condition. Furthermore, the real-time information obtained from the membership value of the granules may provide a resource for situational awareness and for the design of new ecological interfaces to enhance human-system interaction and real-time decision making. The approach presented in this paper is applied to the dynamic model of a reconfigurable aquatic habitat that serves as a small-scale bioregenerative test bed for life support control research. Results show how information generated by the FAM enhances the situation observability of the system.

I. INTRODUCTION

One of the challenges of long-duration spaceflight is the capability of habitation systems to regenerate life support consumables, such as oxygen[1]. Researchers continue to look at *regenerative* life support technologies that would help reduce the frequency of resupply missions and presumably also reduce the cost of such space habitats in terms of logistics. An example is the commissioning of the Water Processing Assembly (WPA) in the U.S. segment of the International Space Station, which recycles waste liquids, including urine, back into potable water. One subset of regenerative technologies considered are *bioregenerative* life support systems (BLSS), which make use of biological processes to transform biological by-products back into consumables. One particular

characteristic of BLSS are the uncertainties generated by the ecophysiological phenomena of the biological processes; these create new challenges for their automation and the real-time assessment by human operators. Switching systems and switched control paradigms are an alternative for the management of such uncertainties[2], [3], [4], [5]; they introduce flexibility into the control path and allow for different control modes depending on the *situation* of the system.

This paper makes use of a perception-based approach to the switched control paradigm. The increasing availability of sensor information and measurements motivates the granular approach of this work. The combination of such sensor information creates sensing spaces in which the operational conditions of systems are found. This work takes advantage of the opportunity to define perceptual elements or granules within these sensing spaces toward integration strategies, automation and assessment of BLSS and other complex socio-technical systems. Furthermore, this approach also allows the implementation of fail-safe and fail-operational mechanisms, critical in any system that involves humans and automation technology. In particular, this work uses intelligent agents based on FAM's made of granular structures composed of n -dimensional non-interactive fuzzy sets [6], [7], [8], [9]. In this work, granular structures [10], [11], [12], [13] define the situations in which each control action governs the system, thus implementing a switched control paradigm to their automation.

The objective of this paper is to explore how the granular structure of FAM-based agents may generate useful information to enhance situation observability and thus potentially provide human operators with resources for real-time decision making. Such exploration is oriented toward the development of methods in user-centered design that take into account situation awareness to inform better ecological interfaces [14], [15]. To this objective, this work makes use of the model of a reconfigurable aquatic habitat as a small-scale bioregenerative life support system. The habitat is purposefully run from a nominal condition into a fail-safe mode, and back to nominal. The specific operating condition of the system is not directly observable from sensor measurements, but from its membership value in the granular structure defined by the FAM.

A. Background

The work presented here may be framed within a 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 system used in this work builds on the use of aquaria, or aquatic habitats, as small-scale units for Earth-based and spaceflight life support research and applications[16], 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) [17], [18], [19], [20], [21], and for ecotoxicological studies in ground-based hardware [16], [22]. Such habitats have made use of on/off control (similar to thermostats) to regulate life support variables that 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[18]. This module also flew in STS-107[20], 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[23]. 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. Section III presents the FAM-based agent architecture, the implementation on the habitat, and elaborates on the simulation 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

The model of the aquatic habitat [24] focuses on the process of respiration. Dissolved oxygen is consumed by the aquatic

organisms at the same time they exhale CO_2 as a by-product. The photosynthesis of plants help to regulate the concentration of CO_2 , generating the oxygen needed by all consumers, aiming to maintain “nominal” concentration levels in the habitat. The life support compounds are stored (dissolved) in the water, medium through which they are exchanged between the organisms. The habitat is a 10-gallon tank divided in four compartments by three separators that allow the water to flow, as shown in Fig. 1.

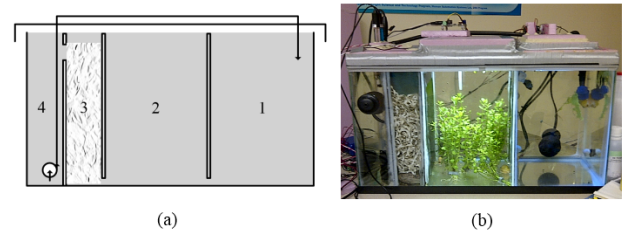


Fig. 1. (a) Recirculation diagram of the habitat; (b) Physical realization of the habitat.

The first compartment houses the animals (consumers) while the second one contains plants (producers) of the *Bacopa Monnieri* species. The third compartment serves the purpose of a mechanical, biological and chemical filter, and the fourth compartment holds the volume of water where the measurements are taken with sensors. The sensors used include dissolved oxygen (DO), pH, oxidation reduction potential (ORP), and water temperature, among others. The water flows through the four compartments; a water pump recirculates it from the fourth back into the first compartment. The first compartment also has a motorized hatch and an aerator that makes the system open (volatile) or closed (non-volatile) to the exchange of gases with the atmosphere; this mechanism can be triggered as a fail-safe mechanism when the DO levels reach a minimum of 2.0 [mg/l]. A neutral-white spectrum LED-lamp is installed in the second compartment to irradiate the plants and thus regulate 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 measurements. The readings from the sensors are processed by a computer/controller. The controller and a pulse width modulation board (PWM) drive LED-lamp power. The computer also positions the hatch, and controls the air and dosifier pumps. The control signals can be the product of control laws or be manipulated through a graphical user interface (GUI).

B. Model of the Reconfigurable Aquatic Habitat

The model of the habitat is described in [24] as the switching system in Eq. 1, where x are substances, such as dissolved oxygen or carbon dioxide, and $[x]$ their concentration in [mg/l].

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

Matrices and vectors for Eq. 1 are:

$$[A]_{cr} = \begin{bmatrix} -\frac{F}{A_1 h} & 0 & 0 & \frac{F}{A_1 h} \\ \frac{F}{A_2 h} & -\frac{F}{A_2 h} & 0 & 0 \\ 0 & \frac{F}{A_3 h} & -\frac{F}{A_3 h} & 0 \\ 0 & 0 & \frac{F}{A_4 h} & -\frac{F}{A_4 h} \end{bmatrix}$$

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

$$[A]_{or} = \begin{bmatrix} -\frac{1}{h}\left(\frac{F}{A_1} + k_v\right) & 0 & 0 & \frac{F}{A_1 h} \\ \frac{F}{A_2 h} & -\frac{F}{A_2 h} & 0 & 0 \\ 0 & \frac{F}{A_3 h} & -\frac{F}{A_3 h} & 0 \\ 0 & 0 & \frac{F}{A_4 h} & -\frac{F}{A_4 h} \end{bmatrix}$$

$$\vec{x} = [x_1 \quad x_2 \quad x_3 \quad x_4]^T$$

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$$\vec{r}_g = \left[\frac{k_v[x]_g}{h} \quad 0 \quad 0 \quad 0 \right]$$

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

$$[B] = \begin{bmatrix} \frac{1}{A_1 h} & 0 & 0 & 0 \\ 0 & \frac{1}{A_2 h} & 0 & 0 \\ 0 & 0 & \frac{1}{A_3 h} & 0 \\ 0 & 0 & 0 & \frac{1}{A_4 h} \end{bmatrix}$$

The assumptions are as follows: (a) the 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. The first two separators have openings with cross sectional areas A_{s_a} , and the third A_{s_b} . The model is implemented making use of the parameters listed in Table I.

The substances x considered are dissolved oxygen (DO), carbon dioxide (CD) and carbonate hardness (kH). The output

equation is $y = [[DO]_4 \quad pH_4 \quad [kH]_4]^T$, where the conversion from $[CD]_4$ into pH is given by [25] $pH_4 = 6.3 - \log([CD]_4/[kH]_4)$. This transformation is valid within a 5-10% accuracy for $6.5 \leq pH \leq 9.5$. 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 rates of production and consumption are presented in Table II.

III. A GRANULAR APPROACH FOR THE AUTOMATION AND ASSESSMENT OF THE AQUATIC HABITAT

This section develops the FAM-based switched approach to control the LED-lamp that regulates the dissolved oxygen concentration in the fourth compartment of the aquatic habitat. The FAM defines the operating conditions and the switching characteristics of the controller, which is encapsulated within the FAM-based agent architecture [7], [8]. Subsection III-A presents a description of the agent and Subsection III-B elaborates on its application to the control of the habitat. 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 implements a switched control approach, assigning a control action to each condition of the system in a modular fashion in the form of (Situation, Controller)[7]. Such switching capability allows for changes and flexibility in the behavior of the system and enables its incremental development and automation. 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. This Subsection presents the FAM-based architecture using terminology from fuzzy systems and fuzzy logic.

TABLE I
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	Surface area 1 st and 2 nd compartments
$A_3 = A_4$	186.69	cm ²	Surface area 3 rd and 4 th compartments
A_{s_a}	12.60	cm ²	Opening area in separators type "a"
A_{s_b}	48.00	cm ²	Opening area in separator type "b"
F	390	l/h	Flow rate of the recirculation pump
$[DO]_g$	8.40	mg/l	Oxygen saturation concentration
$[CD]_g$	0.69	mg/l	carbon dioxide saturation concentration
D	1750	cm/h	Liquid phase diffusion constant
k_v	200	cm/h	Gas transfer diffusion constant

TABLE II
PRODUCTION AND CONSUMPTION RATES FOR \vec{x} IN [MG/H]

	DO_1	CD_1	DO_2	DO_3	CD_3	kH_3
Values	-4	4	23.0	-7.0	7.0	-17

1) *The perception function and granular structure:* Assuming the availability of n measurable variables x_i for $i = 1, 2, \dots, n$ from sensors and their universes of discourse X_i so that $x_i \in X_i \subseteq \mathfrak{R}$, the variables being 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 $X_i^\alpha \subset X_i$, $\alpha = 1, 2, \dots, k_i$. Continuous membership functions describe each one of the subsets as $\mu_{X_i^\alpha}(x_i)$, which are normal and convex [26]. Such partitions comply with the Ruspini condition [27] along their universes of discourse X_i^α :

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

As a result, a number of l possible situations or operating conditions are defined as non-interactive fuzzy sets \tilde{A}_j , for $j = 1, 2, \dots, l$. The l 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.

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

$$\forall j = 1, 2, \dots, l$$

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

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

2) *The control actions:* In the same fashion, the set of control signals $U = \{u_j\}$ is composed of up to l different control laws. Controllers generate signals u_j that correspond to each condition \tilde{A}_j . These control actions form the set $U = \{u_1, u_2, \dots, u_l\}$, with the maximum number of different control signals limited by l . The control signals can be generated by model-based methods or techniques in soft-computing and computational intelligence such as fuzzy logic, neural-networks, genetic algorithms, particle swarms or a combination of them. The error modulation solution in [8] or a similar technique is required for controllers with integral control action (poles in zero).

3) *Correspondence function and the integrated control signal:* With the sets \tilde{A} and U defined, the Correspondence Function Ω can be expressed in pairs as in Eq. 5 or as a rule-base.

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

These pairs indicate the relationship between the fuzzy conditions and the control signals. The resulting fuzzy system is defuzzified with the weighted average technique to obtain an integrated control signal u_I . This is the signal that will drive the actuator or effector of a FAM-based agent in particular. Thus, each actuator or effector in a physical system may become an agent, and therefore be part of a FAM-based multi-agent system. The weights used in the weighted average for u_I are the membership values of each corresponding fuzzy condition, and the weighted arguments are the control signals. The expression for the integrated control signal is therefore:

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

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; (2) the operational conditions that result from the combination of the operating ranges, and their corresponding control actions; and (3) the simulation performed on the habitat for this paper.

1) *Life support signals and their operating ranges:* The life support variables are the DO and pH in the fourth compartment. Their operating ranges and fuzzy membership functions are shown in Fig. 2.

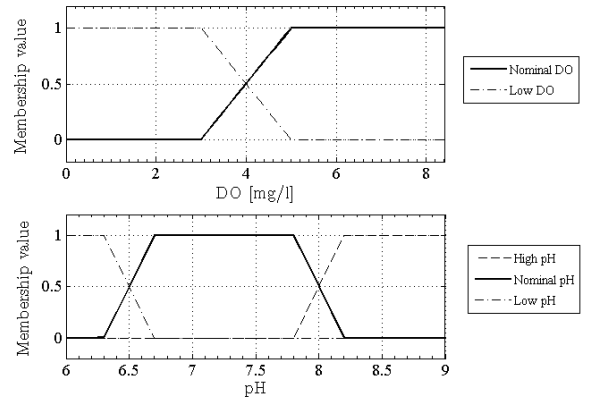


Fig. 2. Fuzzy partitions of the DO and pH variables.

These ranges are defined considering the minimum DO concentration allowed for fresh water animals (2 [mg/l]), and the pH values in which most aquatic organisms may live with low stress[25]. There are two conditions for the DO concentrations: nominal and low. The pH instead has three ranges: nominal, high and low.

2) *Control laws and their operating conditions:* Two control actions are used to drive the power level of the LED-lamp: (1) power on and constant at 100% and (2) a proportional-integral (PI) controller that may dim the lamp in the 0-100% range. The PI controller is used in most of the operating conditions, with $P = 200$ and $I = 50$. The differences of the PI controllers for each operating condition is in the controlled variable and its reference. The Table III shows a representation of the operating conditions and the control actions used in each case. These operating conditions result from the combination of the operating ranges of each variable, according to Subsection III-A. To ensure that the system works correctly, note that the PI controller uses the error modulation technique presented in [8].

TABLE III
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}

The nominal and DO_{min} controllers make use of a reference signal with a duty cycle of 18 hours for every 24. Such duty cycle helps to account for the physiological requirements of the botanical elements. For the nominal condition, the reference alternates between 6.0 [mg/l] and 5.0 [mg/l], while for the DO_{min} the reference switches between 4.5 [mg/l] and 4.0 [mg/l].

3) *Simulation performed on the habitat model:* The simulation presented in this paper explores the transitions between operational conditions triggered by the depletion of kH and the lack of supply from the dosifier pump in the second compartment. This substance is consumed by the bacteria of the biofilter during the process of nitrification. The source of kH is inhibited until day 14 in the simulation, day in which it is restored. The purpose of this simulation is to explore the operating condition transitions of the FAM-based agent and the time response of the life support variables considered. In addition, the simulation also shows the evolution of the membership values of the life support variables in each of the operating conditions, making the system observable from this perspective at any given time. 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, triggering a operating condition transition as shown during day 12 in Figs. 3, 4 and 5. Between days 12 and 15 the system continues to transition into different situations and recovers its nominal condition thereafter, when the kH supply is re-enabled. These results show the dynamics of the transitions from three perspectives. Figure 3 looks at

the evolution of life support variables, DO and pH; Fig. 4 presents the behavior of the LED-lamp; and Fig. 5 shows the membership value of the operational condition of the system over time. The system remains “fail-op/fail-safe” within the conditions defined in Table III.

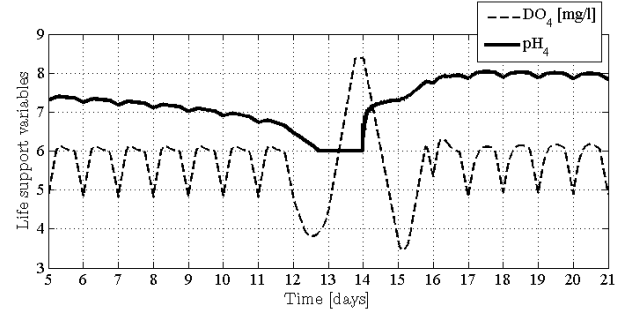


Fig. 3. Evolution of the life support variables during the simulation

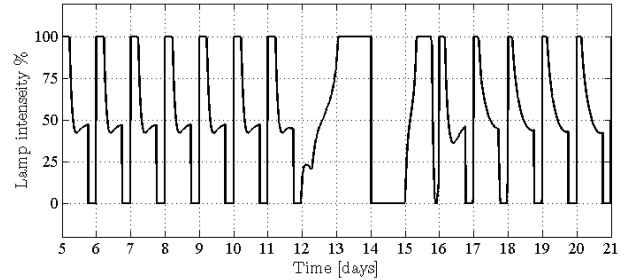


Fig. 4. Lamp intensity percentage in response to controllers enabled during the simulation

From day 5 to about day 11, the system shows consistent and mostly periodic temporal responses as evidenced in Figs. 3 and 4. During this period of time and, without looking at Fig. 5, it can be said that the system remains within a single operating condition, in this case to the “nominal” condition, and seems to be performing well. However, once the first transition enters into effect at around day 12, it becomes harder to assess in which situation is the system until it goes back into “nominal” on day 15. The lack of *situation observability* evident for only two or three signals in this case, is more so true for large-scale socio technical systems composed of many more sensors and signals. Hence, having a granular structure that allows the system to identify its mode of operation becomes helpful not only to allow for automation strategies that adapt the system to various situations, but also to generate new signals that better describe their evolution. This is what Fig. 5 presents in the signals (a) through (f); it shows the history of the situation of the system, and allows to better understand not only the situation in a real-time scenario, but also to perform forensic analysis to Figs. 3 and 4. For example, between days 12 and a slightly after day 15, the system transits between three different operating conditions before going back to “nominal.” These conditions are (not in

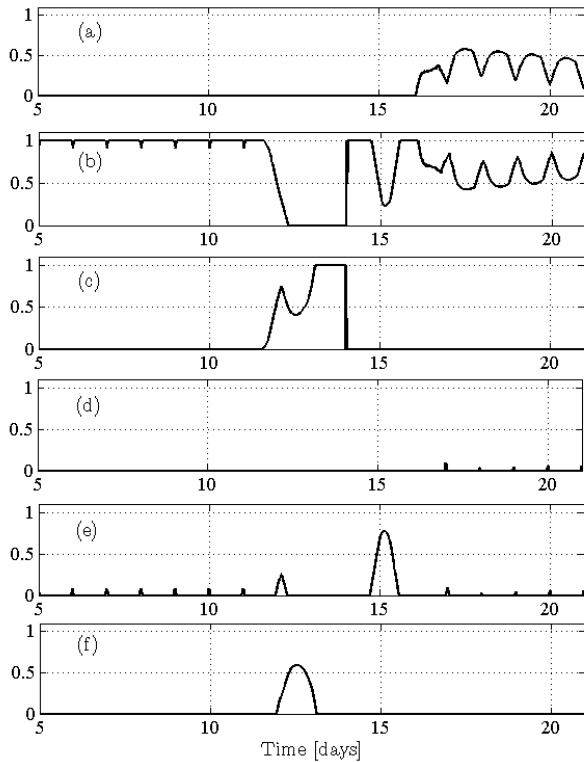


Fig. 5. Membership values of the conditions defined in Table III: (a) Nominal-DO/High-pH; (b) all nominal; (c) nominal-DO/low-pH; (d) low-DO/high-pH; (e) low-DO/nominal-pH; (f) low-DO/low-pH.

chronological order): nominal-DO/low-pH, low-DO/nominal-pH, and low-DO/low-pH. The last of these conditions to enter into effect before the system is dominantly back to “nominal” is low-DO/nominal-pH. Under this condition and according to Table III, the system sets the dissolved oxygen reference value to 3 [mg/l]. Thus, it can be seen in Fig. 3 that the oxygen goes from being in saturation at 8.4 [mg/l] down to about 3.5 [mg/l], just before the last transition back to “nominal” comes into effect. Note also, that in order to bring down the oxygen level from 8.4 [mg/l] to about 3.5 [mg/l], the LED-lamp has to be at 0% (turned off) in Fig. 4 to prevent the plants from generating oxygen and allowing other organisms to consume it. After this transition the system alternates between “nominal” and Nominal-DO/High-pH, which then again according to Table III alternates the controlled variable between the pH level at 8.0 and the dissolved oxygen concentration following the LED-lamp duty cycle.

The forensic analysis of Figs. 3 and 4 described above is possible to most observers because of the information provided by Fig. 5. Such information could be displayed in ecological interfaces to support human operators in real-time decision making tasks; further research will look at how this information may be integrated in interfaces to provide non-expert human users with resources for decision making. The signals generated by the FAM could also be used to assess the evolution of systems into the future, looking at

further applications in diagnosis and prognosis of engineering systems. Beyond BLSS, the granular decomposition of sensing spaces presented in this paper is applicable to a wider range of complex socio-technical systems. Questions then arise on how to manage high-dimensional sensing spaces and what type of methods are required to make this approach practical. The authors suggest the use of other methods in computational intelligence in combination with FAM’s to arrive at solutions applicable to larger-scale systems.

V. CONCLUSION

This paper presented a granular approach to the automation of a small-scale model of a bioregenerative life support system that enhances situation awareness. It presented the dynamic model of a reconfigurable aquatic habitat as a research testbed, and the FAM-based agent architecture an method to automate engineering systems. The FAM acts as the perception function of the agent, decomposing sensing spaces into granular structures. Each granule represents a different operating condition, to which a different control action may be associated. The information generated by the granules may help to enhance situation observability and forensic analysis of dynamic systems. Further research is needed to understand how such information may help to inform better user-centered designs and ecological interfaces. Beyond these, other questions remain about how methods in computational intelligence will help to make this approach practical for larger-scale systems. Applications of such solutions could be useful for data mining in large-scale sensor networks for intelligence, cybersecurity, transportation systems, tactical command and control, and mission control centers, among others.

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