Development and Evaluation of User Interfaces for Situation Observability in Life Support Systems

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Slow-changing characteristics of controlled environmental systems, the increasing availability of sensor information, and the need to avoid human error makes the manual control of these systems ever more challenging to human operators both on the ground and in-flight. Automation systems are better suited to make some of these repetitive and critical tasks more reliable and less time-consuming. However, along with achieving reliable automation, it is beneficial to allow human operators to intervene if a problem occurs within the system, especially in order to take manual control upon anomalies. Ecological interface design, which focuses on the flow of information between the system and the human rather than in particular processes that constitute them, offers a solution to this problem. Such interfaces are user-centered and allow the human operators to gain situation awareness and intervene if necessary. This paper makes use of a granular multi-sensor data fusion method to develop ecological user interfaces for a small-scale life support system. The methodology is applied to the model of a small-scale aquatic habitat working as a ground-based bioregenerative life support system. Three ecological user interfaces were designed and tested on eight non-expert users. Results show the advantage of using situation-rich signals generated by the granular multi-sensor data fusion method that simplifies displays of information to allow for the future design of decision support tools.

I. Introduction

One of the challenges of long-duration spaceflight is the capability of habitation systems to regenerate life support consumables, such as oxygen and water.[1] *Regenerative* life support systems (LSS) offer various options to recycle metabolic byproducts, such as urine, and to achieve an incremental closure of gaseous and liquid material cycles. Such *material closure* increases the autonomy of space habitats and helps reduce the frequency of resupply missions and their overall cost. In fact, on April 10th 2010 in his speech on the "Remarks on Space Exploration in the 21st Century," President Barack Obama challenged:

> "*And we will extend the life of the International Space Station likely by more than five years, while actually using it for its intended purpose: conducting advanced research that can help improve the daily lives of people here on Earth, as well as testing and improving upon our capabilities in space. This includes technologies like more efficient life support systems that will help reduce the cost of future missions.*"

An example of current regenerative LSS is the Water Recovery System (WRS) commissioned in the U.S. segment of the International Space Station (ISS), which recycles waste liquids back into potable (drinking) water. But as researchers continue efforts to integrate regenerative technologies and to incrementally achieve system closure, new challenges arise from their operation. The closure of material cycles not only makes

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possible the interconnection of complex material networks, but may also promote unintended chemical interactions leading to unexpected situations. Such chemical reactions may not susceptible to prediction and are encountered as *anomalies* during operation. Such is the case of the 2010 WRS anomaly caused by the accumulation of dimethylsilanediol (DMSD).[2] In addition, regenerative processes require energy and time to transform wastes and byproducts into consumables. Consequently, their operation imposes considerable workload on human operators. All these challenges, in addition to their slow dynamic response, create vulnerabilities that, if unattended, may translate into human errors, performance deterioration, and failures.

The availability of novel chemical and biological sensors, together with evermore pervasive computational resources, enable the development of monitoring systems to detect anomalies, alleviate human workload, avoid human error, and increase the overall reliability of LSS. This paper makes use of a granular approach to these challenges that enhances situation observability by transforming abundant sensor information in situation-rich signals.[3] This paper makes use of these signals in ecological user interfaces to allow non-expert users to gain situation awareness and intervene. The methodology is applied to the model of a small-scale aquatic habitat working as a closed-loop LSS. The model of the aquatic habitat focuses on the process of respiration. Dissolved oxygen is consumed by snails while exhaling CO_2 as a byproduct. Higher plants regulate the concentration of CO_2 through photosynthesis promoted by an LED lamp, producing the O_2 needed by consumers while aiming to maintain acceptable concentration levels in the habitat. Water serves as the medium in which these quantities are stored, and through which they are exchanged between organisms.

Three ecological user interfaces were designed for the aquatic habitat and tested on eight non-expert users. Experiments and a survey explore the attributes of the interfaces tested. Results show the advantage of using situation-rich signals to simplify displays of information and to enable the development of decision support tools. The approach employs an agent architecture based on fuzzy associative memories (FAM) in an effort to allow for *situation observability* of LSS, *i.e.* the capability of non-expert human operators to probe for information about the situation of the system. Such attribute may also provide operators with operational margin[2] to detect and respond to anomalies in a timely manner.

A. Background

Unlike machines, which accurately perform their tasks as intended unless there is a failure, humans are subject to making mistakes, with *human error* being responsible for at least 60%, and up to 90%, of the accidents reported in domains such as process control, aviation, and health care.[4–6] In particular, a review of military aviation mishaps[7] and a study of accidents in major air carriers found that 88% were caused by human error due to a lack of situation awareness.[8] Such is the case of the Air France flight 447 that intended to transport 216 passengers and its 12 person crew from Rio de Janeiro to Paris on June 1st, 2009.[9] The fact is that beyond purely technology-based problems, a number of issues exist in the integration of humans and automation technology,[10] with lack of *situation awareness* being an important cause of human errors. Situation awareness consists in the "perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status into the near future".[11] This paper focuses on reducing the decision error of non-expert human operators by utilizing situation-rich signals in ecological user-interfaces. This work is part of an effort that aims to inform tools of decision making with methods of computational intelligence and principles in cognitive engineering. The objective is to produce resources for the integration of humans and automation for the operation of such systems.

B. Organization

This paper is divided in five additional Sections. Section II introduces the FAM-based agent architecture used to operate the aquatic habitat. Section III describes the interfaces developed, the simulations performed, and the data collected during human tests. Section IV presents the results and Section V provides observations and some discussion. Finally, Section VI provides concluding remarks.

II. Granular Approach to the Automation and Assessment of LSS

The FAM-based agent architecture is used to automatically drive the lamp power of the aquatic habitat by implementing a switched control approach[12] that assigns a control objective to each situation in which the system may operate in the form of (Situation, Controller).[3] Figure 1 shows a diagram of a single FAM-based agent with a user interface manipulating a single variable in the aquatic habitat. The architecture is composed of a perception function, a set of controllers, and a correspondence function. For completeness, the diagram describes the components of the FAM-based agent consistent with Subsections A, B, and C.

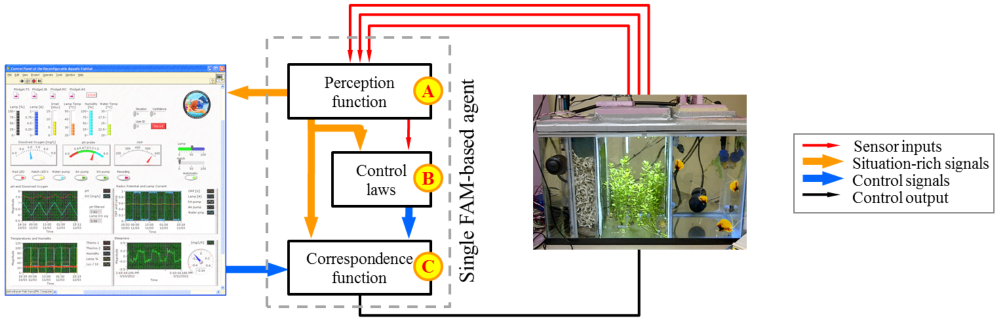

Figure 1. Diagram describing the FAM-based agent architecture and its components

Each actuator may be operated through a FAM-based agent. The perception function acts as a sensor-fusion module, producing the situation-rich signals employed in the user interfaces designed for this paper. Such scheme allows for human-automation coordination by allowing non-experts to operate a dosifier pump that adds a carbonate solution to the water of the habitat. In such a way, experiments are designed to evaluate three user interfaces operated by non-expert users. Further details of the implementation of the FAM-based agent in the automation of the aquatic habitat have been discussed in previous work[3] and are adopted in this paper.

A. Perception Function and Granular Structure

Assuming the availability of n measurable variables x_i for $i = 1, 2, \ldots, n$ from sensors and their universes of discourse X_i so that $x_i \in X_i \subseteq \Re$, the variables being non-redundant and non-interactive: $X_i \neq X_j$; $j = 1, 2, \ldots, n$; $i \neq j$. Each universe X_i is partitioned in k_i subsets, each of which is denoted as $X_i^\alpha \subset X_i$, $\alpha = 1, 2, \ldots, k_i$. Continuous membership functions describe each one of the subsets as $\mu_{X_i^\alpha}(x_i)$, which are normal and convex.[13] Such partitions are *coherent* when complying with the Ruspini condition:[14]

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

As a result, a number of l possible situations or operating conditions are defined as non-interactive fuzzy sets $\tilde{A}_j$, for $j = 1, 2, \ldots, l$. 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. 2, for $l = \prod_{i=1}^{n} = k_i = k_1 \cdot k_2 \cdot \cdots \cdot k_n$.

$$\tilde{A}_j\left(x_1, \ldots, x_n\right) = \min_{\substack{i=1,\ldots,n \\ \alpha=1,2,\ldots,k_i}} \left(\mu_{X_i^\alpha}\left(x_i\right)\right) \tag{2}$$

The set $\tilde{A} = \{\tilde{A}_j\}$ represents the granular structure in which each granule $\tilde{A}_j$ describes a different situation and a percept of the FAM-based agent. The granular structure allows the generation of situation-rich signals useful for the development of ecological user interfaces, on which this paper focuses.

B. Control Signals

In the same fashion, the set of control signals $U = \{u_j\}$ are obtained from up to l different control laws. Controllers generate signals u_j that correspond to each condition $\tilde{A}_j$. These signals may be treated modularly to form the set $U = \{u_1, u_2, \ldots, u_l\}$. The control signals may be generated by model-based methods or techniques in soft-computing. The error modulation solution[15] or a similar technique is required for controllers with integral control action. Considerations on switched control[12,16] should be included in this component of the FAM-based agent and in the correspondence function Ω described in the next Subsection.

C. Correspondence Function and Integrated Control Signal

With the sets $\tilde{A}$ and U defined, the Correspondence Function Ω can be expressed as a rule-base or in pairs (Situation, Control Signal) as in Eq. 3.

$$\begin{aligned} &\Omega : \tilde{A} \rightarrow U \\ &\Omega = \{\Omega_j\} = \left\{ \left(\tilde{A}_j \left(x_1, \ldots, x_n \right), u_j(t) \right) \right\} \end{aligned} \tag{3}$$

The resulting FAM is defuzzified with the weighted average technique to obtain an integrated control signal u_I. This signal drives a single actuator in the system. Thus, each actuator and its controller in a physical system may be conceived as an agent, constituting a FAM-based multi-agent system. The weights used in Eq. 4 are the membership values of each corresponding situation, and the weighted arguments are their corresponding control signals.

$$u_I \left(x_1, \ldots, x_n, t \right) = \frac{\sum_{i=1}^{l} \mu_{\tilde{A}_i} \left(x_1, \ldots, x_n \right) \cdot u_i(t)}{\sum_{i=1}^{l} \mu_{\tilde{A}_i} \left(x_1, \ldots, x_n \right)} \tag{4}$$

III. Interface Development, Simulations, and Human Testing

Experiments in this paper study how non-expert users may detect nominal and off-nominal situations by having them interact with the system using three user interfaces. These have similar designs, displaying information about the system in the form of historic data, instant values, and decision-support elements. While the system is available for experimentation, simulations are used because of the slow response of the aquatic habitat and the time required to run a single test. This allows human subjects to interact with the model for a time equivalent to 21 days during 2-3 minutes of simulation. Although this approach may not be suited for measurements of attention span, for example, it does enable measurements on other attributes of human performance such as perception, working memory, mental models, and action selection. The following two Subsections describe the user interfaces and the simulation performed.

A. Interfaces, Operator Inputs, and User Support Panels

The user interface is shown in Figure 2(a). It allows operators to add kH (carbonate solution) to the aquatic habitat through the input panel of Figure 2(b) depending on their assessment of the situation. A light emitting diode (LED) shows if the pump is active. The input panel also allows the human to monitor the remaining mass kH. If the operators are not able to correct the behavior of the system, they can request the intervention of an expert by pressing the red button. Most of the signals displayed are recorded for analysis.

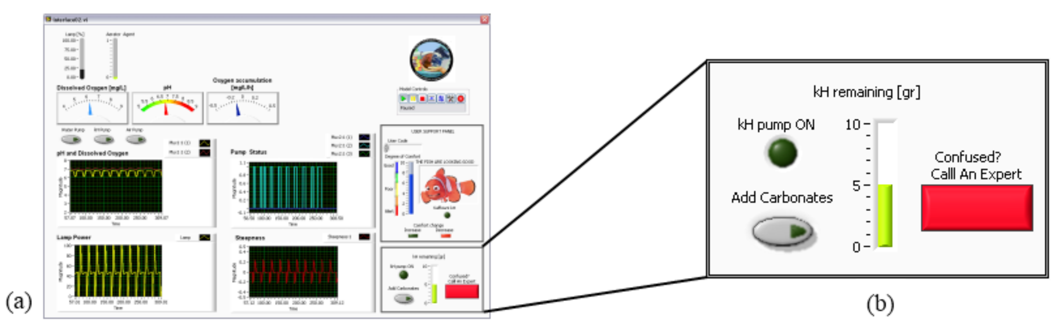

Figure 2. User interface and detail of the input panel

A challenge in developing ecological interfaces is deciding which indicators to employ. If only raw data is used, decision making may become difficult for non-expert operators. In addition, if the interface provides excessive visual information, the user may experience visual overload.[17] Figure 3 shows the three User Support Panels tested. Their elements make use of situation-rich signals generated by the perception function of the FAM-based agent. These elements consist of a visual representation of a fish, a bar showing its degree of comfort, and various LED displaying changes in the degree of comfort. If the situation of the habitat is nominal, the fish shows a “safe” expression with degree of comfort between 0 and 10 as in Figure 3(c). For off-nominal situations, the fish appears to be “unsafe” as in Figure 3(a) and the degree of comfort is zero. Each panel was tested on eight human subjects for the simulation described in the following Subsection.

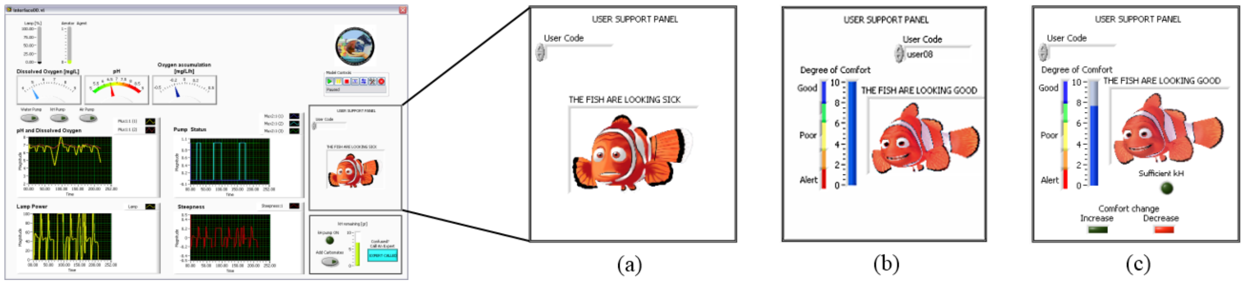

Figure 3. User-support panels (a), (b), and (c).

B. Simulation

The simulation explores operation condition transitions in the aquatic habitat triggered by the depletion of kH. This substance is consumed in the biofilter during the process of nitrification. A FAM-base agent automatically controls the LED lamp of the habitat for various situations. The kH dosifier is manually controlled by non-expert human operators through the user interface. The purpose of the simulation is to observe the integration of non-expert human operators with the automated system as they add kH to the water through the ecological interfaces. The amount of kH available is limited to 10 [gr] of equivalent calcium carbonate. Simulations are implemented with a stiff Mod. Rosenbrock numeric method with maximum and minimum steps of 0.01 and 0.001, respectively. Initial conditions are $[DO] = 8.4$ [mg/l], [CD]=0.69 [mg/l], and [kH]=20 [mg/l].

C. Data Collection and Survey

Each one of the eight participants had the opportunity to interact with the system through interfaces with user support panels (a), (b), and (c). Each user was able to manipulate the activation of the kH pump to keep the system running under “nominal” condition. For non-expert users, “nominal” meant to keep the fish “safe” the most time possible or maintaining its degree of comfort close to 10. With the activation of the kH pump, the participants added carbonate solution in the water from a container that holds 10 [gr]. The intention was to enable non-expert users to maintain the system under “nominal” condition by using the least amount of carbonate solution possible. The response of the life support variables shown in the interfaces system was recorded, as well as the kH remaining at the end of each simulation, and the proportion of time that the system operated under off-nominal condition. In addition, a survey was given to participants in which they answered the eight questions enumerated in Table 1.

	Questions
1:	Rate how clearly you understood the information given in the directions and interfaces.
2:	Rate your understanding of whether the system was nominal or off-nominal.
3:	How well did you understand the system to develop a control approach for each interface?
4:	Which interface made the decision to press the carbonate button easier?
5:	What is the effect of a pH above 7?
6:	Do you think that a “user-support panel” would be realistic in real-world interfaces?
7:	How do you think pushing the “Add carbonate” button changed the system?
8:	What was the most helpful tool in determining when to press the carbonate button?

Table 1. Questions of the survey taken by participants.

IV. Results from Tests with Human Participants

Figure 4 shows examples of the temporal responses of the life support variables monitored during tests with user support panels (a), (b), and (c), respectively. Their purpose is to illustrate how the use of situation-rich signals in decision aids results in improved human-automation coordination with non-expert users.

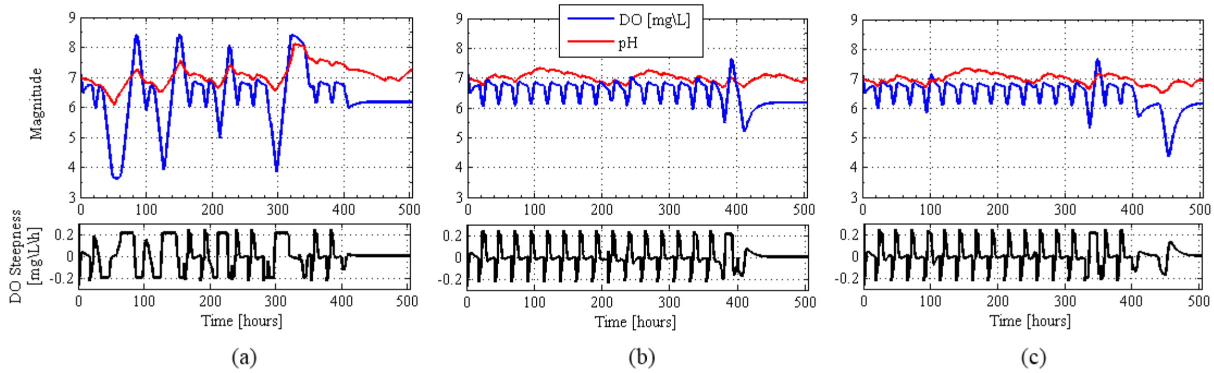

Figure 4. Example of time response of simulations for each interface.

Figure 5 shows the results obtained for the human performance measurements. The graph on the left shows the percent of time each participant incurred in "off-nominal" situation for tests employing a different user-support panel. The graph at the right shows the mass of carbonate solution remaining at the end of each test for all participants. The intention of Figure 5 is to address the integration of non-experts with the automation employed to regulate life support variables in the aquatic habitat. Such observations measured how well non-experts performed by making use of user support panels (a), (b), and (c).

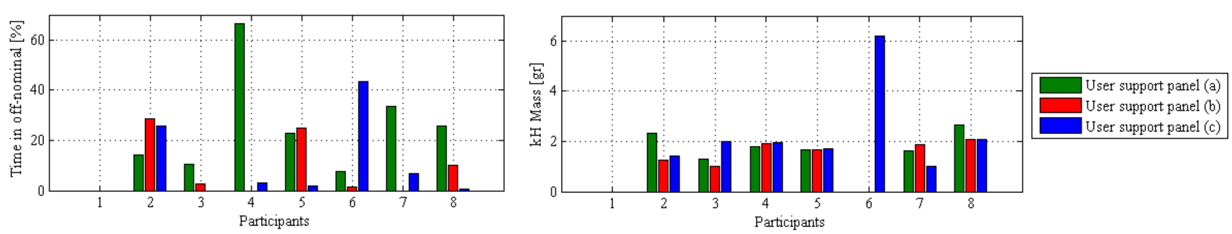

Figure 5. Measures of participant performance for the user support panels.

Figure 6 shows how participants perceived their general understanding of the situation of the aquatic habitat by assigning a value between 0 and 10 to Questions 1 through 3. The graph shows the percentage of responses supporting different levels of understanding. Levels not shown registered 0% of responses.

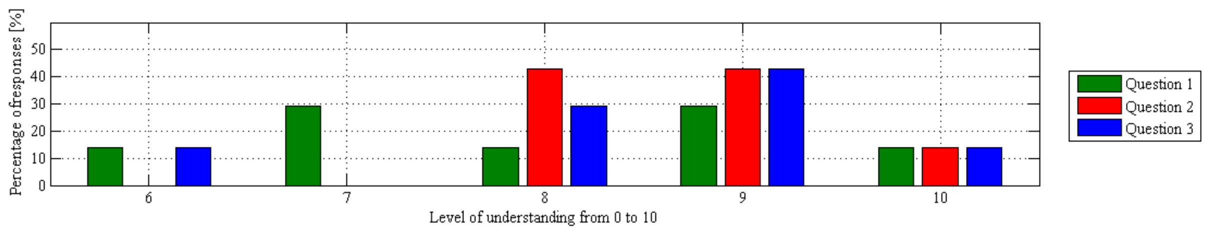

Figure 6. Responses to survey questions 1 through 3.

Tables 2, 3, and 4 present the responses to survey Questions 4 through 8. The options for question 7 were: (A) it made the fish unsafe, (B) it made the fish safe, (C) it increased pH, (D) it decreased pH, (E) A and C, (F) B and C, (G) A and D, (H) I don't know.

Question 4	Responses	Question 5	Responses	Question 6	Responses
User-support panel (a)	14%	A "safe" fish	71%	Yes	86%
User-support panel (b)	57%	An "unsafe" fish	0%	Neutral	0%
User-support panel (c)	29%	I don't know	29%	No	14%

Table 2. Answers to questions 4, 5, and 6.

Option	A	B	C	D	E	F	G	H
Responses	0%	57%	0%	0%	0%	29%	14%	0%

Table 3. Answers to question 7.

Option	The fish	Comfort bar	pH scale	kH left	Comfort LED	kH LED	Graphs
Responses	14%	57%	0%	0%	14%	14%	0%

Table 4. Answers to question 8.

V. Discussion

The examples in Figure 4 illustrate how participants are able to achieve a more regular behavior with user support panels (b) and (c) given the availability situation-rich signals. Such observation is supported by the responses of participants to Question 4 (Table 2), which results in 57% evaluating user panel (b) as "easier" to decide when to activate the kH pump. In fact, in the answer to Question 8 (Table 4), 57% of participants chose the "Degree of Comfort" bar to be the most helpful indicator to determine if the situation was nominal or off-nominal, which is part of the user support panels (b) and (c). Such result contrasts with the expectation that the image of the fish would be more useful for non-expert users. This may be due to the fact that the fish would change its state only when the system would transition into off-nominal, and not before. In future interfaces, this transition could be associated to the maximum value in the degree of comfort, making it change when this variable falls below 10, providing the non-expert user with operational margin before an off-nominal condition takes place.

Following the "Degree of Comfort" bar are the image of the fish, the LED showing comfort change, and the LED indicating enough kH. Interestingly, none of the participants used the pH indicator as a variable to help maintain nominal condition, nor did they observe the graphs nor the mass of carbonate solution left. Such result supports the tendency of non-expert users to make use of displays that offer cues about the state of the system without specifically describing internal variables. Such is the principle in ecological interface design, which focuses on the flow of information between the system and the human rather than in particular processes that constitute them.[18,19]

In the same direction, the answers to Question 7 (Table 3) provide evidence of the associations made by participants between the action of adding carbonate solution to the water and its effect on the situation of the system. In this case, 57% of the participants became aware that by adding carbonate the fish would stay "safe," but only 29% understood that by activating the kH pump they would also increase the pH. Yet another observation relevant to ecological interface design is the result shown in Figure 5. This result highlights the fact that the user-support panel (b) resulted in less time in off-nominal condition for most participants than other interfaces. Such observation is made from the fewer number of red-color bars in the left-side graph of Figure 5.

Because the user-support panel (c) included more indicators to assist non-expert users, it was expected that such interface would achieve better results. However, it may be due to "visual overload" caused by the additional LED indicators that participants tended to perform better with user-support panel (b). In fact, the mass of kH remaining shown in the right-side graph in Figure 5 suggests that the performance of participants was more consistent with user-support panel (b); it shows a similar value for most of them.

In general, participants were able to develop an apparently good understanding of how to interact with the system, according to Questions 2 and 3, despite the responses obtained to Question 1 (Figure 6). This may also be supported by the responses to Question 5 (Table 2) with the majority of participants understanding the benefit of a pH above 7. Finally, answers to Question 6 (Table 2) provides insights into the potential acceptance of panels making use of situation-rich signals by having 86% participants approving the usability of user support panels in realistic LSS applications. A question raised for future research is how may training change user acceptance to various interface designs employing situation-rich signals, and what new mental models may develop from human-system interaction over time.

VI. Conclusion

This paper presented the development and testing of ecological user interfaces for situation observability in LSS. It made use of situation-rich signals generated by the FAM-based agent architecture to develop ecological user interfaces for a small-scale life support system. The methodology is applied to the mathematical model of an aquatic habitat working as a closed-loop LSS. Three ecological user interfaces were developed and tested on eight non-expert users. Results show the advantages of using situation-rich signals to simplify displays of information to enable future decision support tools. Future work will focus on efforts in data abstraction for mission control settings, on how training may affect the acceptance of ecological user interfaces employing situation-rich signals, and on the application of this approach in monitoring and decision support tools for current and future LSS, for ISS and the emerging commercial space sector.

Acknowledgments

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