Monitoring the State of a Ubiquitous Robotic System: A Fuzzy Logic Approach

Donatella Guarino and Alessandro Saffiotti

***Abstract*— A trend is emerging in the fields of ambient intelligence (AmI) and autonomous robotics, which points in the direction of a merger between these two fields. The inclusion of robotic devices in AmI system, sometimes named *ubiquitous robotics*, makes one of the hard problems in this field even harder: how can we provide a comfortable, natural interface between the everyday user and a complex system which consists of a large multitude of highly heterogeneous devices? In this paper, we address a specific, important aspect of this problem: to monitor the state of the ubiquitous system by the user of the system. The solution that we propose is based on two mechanisms: an *expression-based semantics* to represent in a uniform way the status of heterogeneous devices; and a *common interface point* to aggregate the information from all devices into a summary status presented to the user. For both mechanisms, we propose to use the tools of fuzzy logic. We justify this choice by arguments grounded in the semantics and formal properties of fuzzy logic. We also illustrate our approach on a specific type of ubiquitous robotic system called *Ecology of Physically Embedded Intelligent Systems*, or PEIS-Ecology.**

***Index Terms*— Ambient intelligence, Ubiquitous robotics, Network robot systems, Human-robot interaction, Cooperative systems, Robot ecology.**

I. INTRODUCTION

There is a marked tendency today toward the embedding of many ubiquitous, intelligent, networked robotic devices in our homes and offices. This tendency is witnessed by the growing interest in the field of ambient intelligence and smart homes, as well as by the new emerging fields of intelligent spaces [1] and ubiquitous robotics [2], [3], [4]. The development of these ubiquitous domestic systems is often motivated by the desire to improve the quality of life of citizens in general, and of elderly people in particular. In this context, it is essential that this development is accompanied by the development of suitable *interfaces* that ensure the usability and acceptability of these systems [5], [6], [7].

It has been noted that the problem of interfacing with an ubiquitous domestic system is different from, and more complex than, the conventional human-computer interface problem. Although a typical ubiquitous system consists of a collection of heterogeneous, inter-connected devices, it should be perceived by the user as one system and the interaction should obey one set of rules — as close as possible to the interaction rules which are natural to the user. This entails two major challenges. First, the user should interact with all the devices through one and the same virtual interface point, thus hiding the underlying *complexity* of the whole system [7]. (Although the interface point is virtually unique, it can be physically instantiated at different locations and via different modalities, depending on the context [8], [6].) Second, the interaction should be based on a uniform model, thus hiding the *heterogeneity* of the devices [9].

In this paper, we address a specific, important case of this interface problem: to monitor the state of the ubiquitous (AmI or robotic) system by the everyday user of the system. Even in this restricted case, we still need to address the complexity and heterogeneity problems above.

Figure 1 graphically illustrates the approach presented in this paper. First, status information for each device in the system is translated to a common representation, endowed with a uniform semantics independent on the nature of the devices. Second, the status information from all devices is combined into an overall status that gives a summary view of the entire system. Finally, this overall status is presented to the user via a suitable choice of modalities, including synthetic actors, sounds, lights, etc.

In the work presented here, we use fuzzy logic techniques to address the two problems represented by question marks in the figure: to represent status information, we use fuzzy values under a desirability interpretation [10]; and to represent the combination of individual status information into an overall one, we use fuzzy propositional formulas. In addition, we associate fuzzy (desirability) values with human-understandable expressions, like ‘sad’ or ‘happy’, which are visualized to the human user via an animated character. Although fuzzy logic has been previously applied to ambient intelligence settings [11], [12], [13], we are not aware of other uses of fuzzy logic to provide a uniform way to encode, combine and visualize the status of an ambient intelligence or ubiquitous system.

In the rest of this paper, we present our proposed approach in the above direction. Our approach is in principle applicable to any ambient intelligent or ubiquitous system. In this work, however, we apply it on a specific system for ubiquitous robotics, named *Ecology of Physically Embedded Intelligent Systems*, or PEIS-Ecology. The next section provides a reminder on PEIS-Ecology.

II. THE PEIS-ECOLOGY APPROACH

The concept of PEIS-Ecology, originally proposed by Saffiotti and Broxvall [4], combines insights from the fields of ambient intelligence and autonomous robotics, to generate a new approach to the inclusion of robotic technology into smart environments. In this approach, advanced robotic

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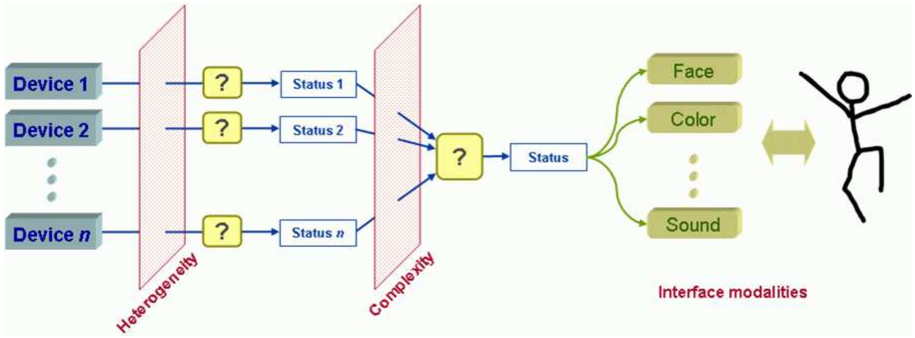

Fig. 1. Schematic illustration of the two aspects of the common interface problem: how to represent the status of heterogeneous devices in a uniform way; and how to combine the status of each device into an overall status information according to a possibly complex combination pattern.

functionalities are not achieved through the development of extremely advanced robots, but rather through the cooperation of many simple robotic components. The concept of a PEIS-Ecology builds upon the following ingredients.

First, any robot in the environment is abstracted by the *uniform notion* of a PEIS (Physically Embedded Intelligent System), which is any device incorporating some computational and communication resources, and which is capable of interacting with the environment via sensors and/or actuators. A PEIS can be as simple as a toaster and as complex as a humanoid robot. In general, we define a PEIS to be a set of inter-connected software components, called PEIS-components, residing in one physical entity. Each component may include links to sensors and actuators, as well as input and output ports that connect it to other components in the same or another PEIS.

Second, all PEIS are connected by a *uniform communication model*, which allows the exchange of information among PEIS, and can cope with them joining and leaving the ecology dynamically.

Third, all PEIS can cooperate using a *uniform cooperation model*, based on the notion of linking functional components: each participating PEIS can use functionalities from other PEIS in the ecology in order to compensate or to complement its own. We define a PEIS-*Ecology* to be a collection of inter-connected PEIS, all embedded in the same physical environment.

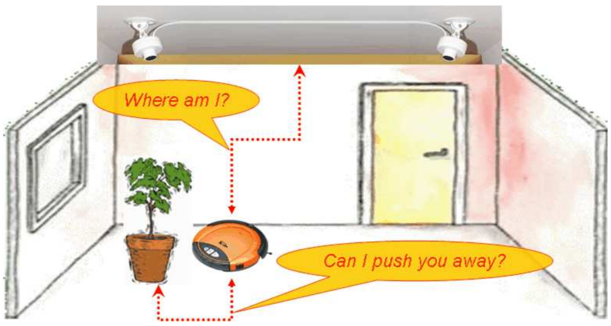

Fig. 2. A simple PEIS-Ecology consisting of a vacuum cleaner, an overhead tracking system, and a plant.

As an illustration, consider the autonomous vacuum cleaner (PEIS) in Figure 2. By itself, the simple device can only use basic reactive cleaning strategies, because it does not have enough sensing and reasoning resources to assess its own position in the home. But suppose that the home is equipped with an overhead tracking system, itself another PEIS. Then, we can combine these two PEIS into a simple PEIS-Ecology, in which the tracking system provides a global localization functionality to the vacuum cleaner. Suppose then that the vacuum encounters a plant, and that the plant is equipped with a micro-PEIS (e.g., a mote) able to communicate its properties — e.g, size, humidity, and type of support (static or wheeled). Then, the vacuum can use these properties to decide whether it can push the plant away and clean under it.

In our realization of a PEIS-Ecology, the PEIS rely on a distributed middleware to communicate and cooperate, called the PEIS-middleware. The PEIS-middleware implements a distributed tuple-space on a P2P network: PEIS exchange information by publishing tuples and subscribing to tuples, which are transparently distributed by the middleware. By stipulation, each PEIS also provides a set of standard tuples, e.g., to announce its physical appearance or the functionalities that it can provide. More details on the PEIS-middleware can be found in [14] and [15].

III. Expression-Based Semantics

The first of the two challenges listed in the Introduction is how to address the *heterogeneity* problem: that is, how to represent in a uniform way the status information about different, heterogeneous devices in the ubiquitous system — in our case, about different PEIS in a PEIS-Ecology.

For most PEIS, the PEIS has an internal status from which we can distinguish "normal" and "abnormal" conditions. Different PEIS, however, have different ways to represent their status, and different variables and physical quantities are involved in these normal or abnormal conditions. For instance, in the above scenario, the plant may need watering, or the cleaning robot may be running out of batteries: the relevant measures are, respectively, the ground humidity and the battery voltage.

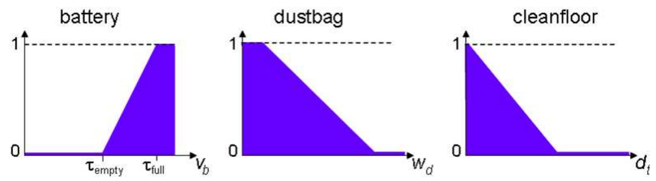

Fig. 3. Fuzzy satisfaction predicates for the vacuum cleaner

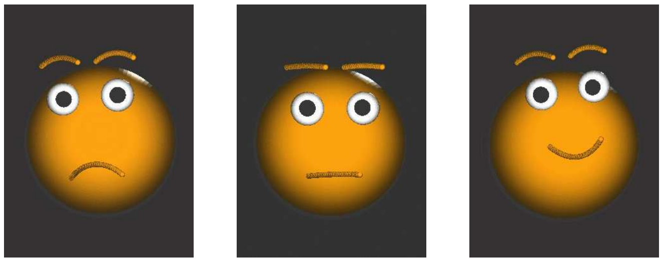

Fig. 4. Visualization of the satisfaction status for three different values: 0.2 (very sad, left); 0.6 (rather worried, middle); 1.0 (quite happy, right).

In order to provide a uniform way to treat these conditions, we consider an abstract notion of "satisfaction", and we encode the degree of satisfaction by a fuzzy predicate with values in the $[0, 1]$ interval. In our example, both the plant and the vacuum cleaner would have associated fuzzy predicates, say plant-ok and vacuum-ok, whose values range from total dissatisfaction (0) to total satisfaction (1). This use of fuzzy predicates is compatible with the semantics given to fuzzy logic in terms of desirability values [10], [16]: the degree of satisfaction of a PEIS in a given state corresponds to the degree by which that state is *desirable* for that PEIS.

To illustrate this point, consider again the vacuum cleaner. This includes a PEIS-component called *battery-manager*, which manages the battery and measures its voltage v_b. From the point of view of having a charged battery, then, we can represent the degree of satisfaction of the vacuum cleaner by the fuzzy predicate battery represented in Figure 3 (left), where the τ_{empty} and τ_{full} values correspond to the conditions of the battery being fully empty and fully charged, respectively. (The dustbag and cleanfloor predicates will be commented in the next section.)

The use of fuzzy predicates allows us to represent in a uniform way the status of all PEIS in a PEIS-Ecology, irrespective of their internal details and on the physical quantities which this status relates to. As we shall see, this also allows us to use the mechanisms of fuzzy logic to combine the satisfaction of several PEIS inside the ecology into a summary satisfaction status for the whole ecology.

Since our goal is to convey the satisfaction status to the user, we endow the satisfaction predicates with what we call an *expression semantics*. We associate the truth value of these predicates to human-understandable expressions. This semantics is informally defined by the following stipulations:

- the value 0 is associated to a 'sad' expression;
- the value 1 is associated to a 'happy' expression; and
- for any $x, y \in [0, 1]$, if $x > y$ then the expression associated to the value x is 'happier' than the expression associated to the value y.

These expressions can be communicated to the human user via a specific interface modality. In our prototype implementation, we use facial expressions of a simple animated character. These expressions are generated by changing the geometric parameters of the face, and cover a continuous range from fully sad (0) to fully happy (1). Figure 4 shows three expressions corresponding to three different degrees of satisfaction.

In addition to providing a uniform semantics with respect to the heterogeneity of the devices being monitored, the expression semantics is also uniform with respect to the modality used to convey the status information to the user. For instance, we could use colors of a given artifact to convey expressions, provided that we have an intuitive mapping between colors and perceived expressions — or the corresponding emotions. Mappings of this type are studied in psychology and design [17], [18], and are outside the scope of this article. However, the possibility offered by the expression semantics of rendering the status information using different modalities is especially interesting in an ubiquitous or ambient intelligence setting: in general, the choice of the most adequate modality depends on several contextual conditions, including the user's current location, their activities, ambient light and noise level, and so on.

IV. Common Interface Point

Now that we are able to represent in a uniform way the satisfaction status of each individual PEIS in a PEIS-Ecology, we can turn our attention to the second challenge listed in the Introduction. How can we combine all this information into one single, overall item of information that gives the user an overall view, at a glance, of the status of the entire PEIS-Ecology? Three factors contribute to complicate this problem.

(a) The combination can be more complex than simply taking the average (or minimum) of all the individual values of satisfaction. For instance, the fact that the batteries in the vacuum cleaner are discharged indicates a problem if the floor needs to be cleaned, but it does not if the floor is already clean.
(b) It should be possible to compute this combination in a modular and decentralized way, to account for the distributed nature of a PEIS-Ecology.
(c) It should be possible to trace back the source of a low satisfaction status, and present this to the user to identify the origin of a problem and correct it.

In this section, we show that the use of fuzzy logic can properly address all these aspects.

In our framework, we encode combinations of satisfaction conditions by using propositional formulas in fuzzy logic, built upon the fuzzy predicates that we used to encode the individual satisfaction conditions. We then evaluate the overall satisfaction degree by computing the corresponding degree of truth of that formula.

Consider again our vacuum cleaner. In addition to the *battery-manager* mentioned above, it also includes two more PEIS-components: a *dustbag-sensor*, which determines the fill level of the dustbag using an internal sensor; and a *dirt-sensor*, which maintains a cumulative value of how much dirt was encountered in the last n minutes of operation. Correspondingly, the vacuum cleaner includes the three fuzzy satisfaction predicates: $\mathsf{battery}$, discussed above; $\mathsf{dustbag}$, true if the dustbag is empty; and $\mathsf{cleanfloor}$, true if no remaining dirt was detected on the floor. Figure 3 shows a possible definition of these fuzzy predicates.

The satisfaction of the vacuum cleaner, then, can be represented by the logical formula $(\mathsf{battery} \wedge \mathsf{dustbag}) \vee \mathsf{cleanfloor}$, that is, either the vacuum cleaner is in good operating conditions (battery charged and dustbag not full), or there is no remaining dirt to clean. Assume further that the plant includes two PEIS-components, one that measures the humidity and one that measures the temperature; and that it has two corresponding fuzzy predicates, respectively named $\mathsf{humidity}$ and $\mathsf{temperature}$ with the obvious definition. Then, the overall satisfaction status of our small PEIS-Ecology can be represented by the formula Φ given by:

$$\Phi = ((\mathsf{battery} \wedge \mathsf{dustbag}) \vee \mathsf{cleanfloor}) \wedge (\mathsf{humidity} \wedge \mathsf{temperature}) \quad (1)$$

The overall satisfaction degree of our ecology at time t, then, is obtained by computing the truth value of Φ at time t, which we denote $\Phi(t)$. This is computed from the truth values of the individual fuzzy predicates according to the usual rules of fuzzy logic:

$$\Phi(t) = ((\mathsf{battery}(t) \otimes \mathsf{dustbag}(t)) \oplus \mathsf{cleanfloor}(t)) \otimes (\mathsf{humidity}(t) \otimes \mathsf{temperature}(t)) \quad (2)$$

where $\otimes$ is any T-norm, and $\oplus$ is the corresponding T-conorm [19], [20]. Figure 5 graphically illustrates this computation, in the case in which we use the min/max pair for $\otimes/\oplus$.

The use of fuzzy propositional logic to encode combinations of satisfaction conditions has three advantages. First, it allows us to address desideratum (a) above, since we can use the full expressive power of propositional calculus to represent complex combination patterns. Second, we have a wide variety of $\otimes/\oplus$ operators to chose from, depending on which behavior we want to model. For instance, if in our application having two PEIS with low satisfaction values should be regarded as worst than having just one, we should use a strict T-norm (e.g., product), so that the combination of two low values would be even lower. Third, for any operator choice, we are guaranteed that the values computed are semantically consistent with our interpretation of the satisfaction values, since this interpretation is consistent with the desirability interpretation of fuzzy logic [10].

Turning now to desideratum (b) above, we notice that in general a PEIS-Ecology has a hierarchical structure. In fact, each PEIS consists of a set of more elementary PEIS-components: in our example, the vacuum cleaner PEIS has three components, and the plant PEIS has two components.

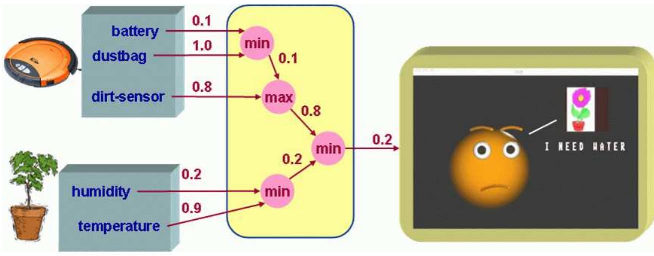

Fig. 5. Computing the overall state of a simple ecology from the state of each individual component. An icon of the main culprit of the low satisfaction state is shown to the user.

Moreover, PEIS in the ecology might be grouped into sub-ecologies according to some structure. An obvious grouping can be induced by the structure of the environment, e.g., all the PEIS in the kitchen can form the kitchen sub-ecology, and all the sub-ecologies in the house can form the overall house PEIS-Ecology. Notice that membership to sub-ecologies may change dynamically: for instance, the vacuum cleaner may exit the kitchen sub-ecology and enter the bedroom one during its operation. A similar hierarchical and dynamic structure may characterize most other systems of ubiquitous robotics and ambient intelligence.

In practice, it is unrealistic to assume that equation Φ is represented and computed at one single place in the PEIS-Ecology — that is, at the interface point. This would require that the interface point has individual connections to each individual PEIS-component in the PEIS-Ecology; and that the representation of the Φ formula inside the interface point is updated every time a PEIS joins or leaves the ecology. A more efficient and modular solution is to distribute the representation of the Φ formula in the PEIS-Ecology. In our implementation, we keep the formula that combines the satisfaction status of all the PEIS-components of a given PEIS inside that specific PEIS. The truth value is computed locally inside the PEIS, and the result is propagated outside to be further combined. Thus, formula (1) above is actually split as follows:

$$\begin{aligned} \phi_1 &= (\mathsf{battery} \wedge \mathsf{dustbag}) \vee \mathsf{cleanfloor} \\ \phi_2 &= \mathsf{humidity} \wedge \mathsf{temperature} \\ \Phi &= \phi_1 \wedge \phi_2 \end{aligned}$$

where ϕ_1 is represented inside the vacuum cleaner, and ϕ_2 is represented inside the plant. Correspondingly, the computation of (2) is actually split as:

$$\begin{aligned} \phi_1(t) &= (\mathsf{battery}(t) \otimes \mathsf{dustbag}(t)) \oplus \mathsf{cleanfloor}(t) \\ \phi_2(t) &= \mathsf{humidity}(t) \otimes \mathsf{temperature}(t) \\ \Phi(t) &= \phi_1(t) \wedge \phi_2(t) \end{aligned}$$

where each computation is performed locally inside the corresponding PEIS.

It is worth to emphasize that the ability to freely distribute the computation across PEIS comes from the fact that T-norms and T-conorms are associative and commutative. If we used, for instance, an average operator, this distribution would not been possible in general.

Fig. 6. Two views of the experimental testbed. Left: the expressive face interface shown on a TV screen. Right: A *moteiv* Tmote used to monitor temperature and humidity of a plant.

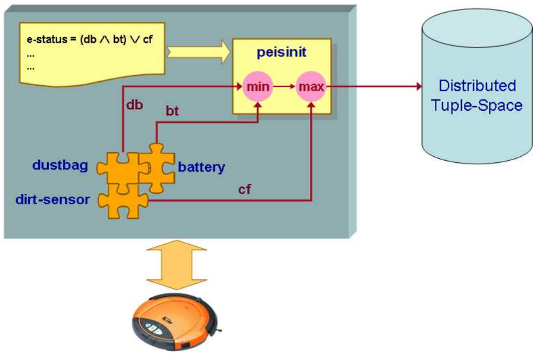

Fig. 7. Each PEIS computes its local satisfaction status in its "peisinit" component.

The last desideratum above (c) can also be met using fuzzy logic. Assuming that we use the min/max pair for $\otimes/\oplus$,[1] the formula Φ that encodes the overall status of the PEIS-Ecology can be put in Disjunctive Normal Form [21]:

$$\Phi = \bigvee_{i=1}^{n} \left(\bigwedge_{j=1}^{k_i} l_j \right)$$

where l_j are literals. Then, we can find the literal which is the main "culprit" of a low overall value of satisfaction by first finding the conjoint i with the lowest truth value, and then finding the literal l_j with the lowest truth value inside that conjoint. The "culprit" PEIS-component is simply the one associated to that literal. If there is more than one literal with the lowest value, all the corresponding PEIS-components are equally responsible for the un-satisfaction situation.

In practice, the literal (PEIS-component) with the lowest value can be found by following the lowest values backward in the computation tree. In the example in Figure 5, this is the humidity predicate in the plant PEIS. In our implementation, each PEIS has an associated graphical icon, and each of its components has an associated text that gives an explanation of why it would be unsatisfied. This icon and text are visualized in the graphical interface in order to give the user an immediate indication of what is going wrong: in Figure 5, the artificial character is visualizing the plant's icon with the explanatory text "I need water".

V. An Experimental System

In order to verify the viability of the ideas presented above, we have performed a few simple experiments in the framework of our PEIS-Ecology testbed. This is a small bachelor apartment (about $25\,\mathrm{m}^2$), which we call the PEIS-Home (see Figure 6). The PEIS-Home has a living room, a bedroom, and a kitchen. It is equipped with a number of PEIS, including mobile robots, a smart refrigerator, ceiling cameras, a media center, and others. The PEIS-Home also includes a few everyday objects which have been converted into PEIS by the inclusion of small computing and communication devices. Figure 6 (right) shows a plant equipped with a Moteiv "Tmote Sky" mote that incorporates temperature and humidity sensors, and can exchange tuples with all the PEIS in the PEIS-Ecology.

Each PEIS produces its satisfaction information by regularly publishing tuples in the PEIS-Ecology distributed tuple-space — this is the standard communication means in a PEIS-Ecology. These tuples have as key the reserved key `e-status`, and as values the current satisfaction value (an arbitrary float between 0 and 1) together with an explanatory text (a string). The `e-status` tuples are generated inside the PEIS by a special component, called `peisinit`, which is responsible for the initialization, maintenance, and configuration activities for that PEIS. We have extended `peisinit` to also: (a) combine the satisfaction values provided by the components inside the PEIS into an overall value, according to a given combination formula, like ϕ_1 in the above example; (b) generate an explanatory string derived by the component with the lowest value; (c) publish a `e-status` tuple that contains that value and that string. Figure 7 shows the above elements for the vacuum cleaner PEIS. The combination formula and the explanation strings are currently pre-compiled into the PEIS, but we plan to eventually specify them as parameters in XML format. As for T-norm and T-conorm, we currently use the min/max pair.

To visualize the status of the PEIS-Ecology, we have implemented a simple interface point that subscribes to all the `e-status` tuples, combines them into an overall satisfaction value, and visualizes this value by a facial expression. If the satisfaction value is below a given threshold, the icon and the explanatory text of the "culprit" are also visualized as explained above. Figure 6 (left) shows the interface visualized on the PEIS-Home TV set. In our future work, we plan to explore the use of other modalities to realize expressions (e.g., [22]).

VI. Conclusions

Expression-based semantics provide a uniform way to represent status information across a highly heterogeneous ubiquitous system, to summarize this information, and to convey it to the user. In this paper, we have shown that fuzzy logic provides an adequate set of tools to convert

[1] This assumption is not strictly needed, but it simplifies the computation described below.

expression-based semantics in an effective and well-founded computational framework. While we have used our PEIS-Ecology testbed as an illustrative example, we believe that the principles and techniques introduced in this paper can as well be applied to any system for ubiquitous robotics or ambient intelligence.

The study of expression-based semantics has just started, and many issues remain to be investigated. Among the most urgent ones: How can we weight the satisfaction values to take into account the user's needs, priorities and preferences? How can we extend the expression-based semantics to other types of states, like danger or surprise? How can we convey "expressions" using other modalities, like sound or color?

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