The PEIS-Ecology Project: a progress report

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***Abstract*— The concept of Ecology of Physically Embedded Intelligent Systems, or PEIS-Ecology, combines insights from the fields of ubiquitous robotics and ambient intelligence to provide a new solution to building intelligent robots in the service of people. While this concept provides great potential, it also presents a number of new scientific challenges. The PEIS-Ecology project is an ongoing collaborative project between Swedish and Korean researchers which addresses these challenges. In this paper we introduce the concept of PEIS-Ecology, discuss its potential and its challenges, and present our current steps toward its realization. We also point to experimental results that show the viability of this concept.**

Keywords— Network robot systems, Ubiquitous robots, Cooperative robotics, Ambient intelligence, Autonomous robots.

I. INTRODUCTION

In the classical view of autonomous robotics, the robot and the environment are seen as two distinct entities. The environment is usually assumed to be non-deterministic and only partially observable, and the robot can only interact with it through its noisy sensors and unreliable actuators. This view is often assimilated to a two-player antagonistic game, in which the robot has to find a strategy to achieve its goal in spite of the "moves" taken by the environment.

In the project presented in this paper, we take an ecological view of the robot-environment relationship [6]. We see the robot and the environment as parts of the same system, which are engaged in a symbiotic relationship. We assume that robotic devices are pervasively distributed in the environment in the form of sensors, actuators, smart appliances, active tagged objects, or more traditional mobile robots. We further assume that these devices can communicate and collaborate with each-other by providing information or by performing actions. We call a system of this type an *Ecology of Physically Embedded Intelligent Systems*, or PEIS-Ecology.[1]

As an example, consider a robot trying to grasp a milk bottle. In a PEIS-Ecology, this robot would not need to use its camera to acquire the properties of the bottle (shape, weight, etc.) in order to compute the grasping parameters — a task which has proved elusive in decades of robotic research. Instead, the bottle itself, enriched with an IC-tag, can hold this information and communicate it to the robot.

The PEIS-Ecology approach is a witness of a general vision which is becoming rather popular in our field: to abandon the idea of having one extremely competent isolated robot acting in a passive environment, in favor of a network of cooperating robotic devices embedded in the environment. This vision has has been spelled out under different names, including network robot systems [16], intelligent space [12], sensor-actuator networks [5], ubiquitous robotics [10], and still others. Like most of the these approaches, the PEIS-Ecology approach has a great potential to bring robotic technologies inside our homes and working places, in the service of humans and to improve the quality of life. Before this potential can be fully exploited, however, there are several fundamental research challenges that need to be addressed. The purpose of this paper is to discuss these challenges, and to present the initial solutions that we have developed in the context of a collaborative project between Sweden and Korea.

The rest of this paper is organized as follows. In the next section, we briefly recall the concept of PEIS-Ecology. In the following two sections we discuss the potentials of this concept and the research challenges that it entails, respectively. In section V we summarize the current progress in the study of PEIS-Ecology which is pursued in our project. Finally, in section VI we outline some future directions.

The goal of this paper is to give a general overview of the concept of PEIS-Ecology and on our progress toward its practical realization. Accordingly, we do not present any technical details or show full experiments in this paper, but we shall refer the reader to the relevant papers in which these details and experiments are reported. More information can also be found at the project web site `http://aass.oru.se/~peis/`.

II. THE CONCEPT OF PEIS-ECOLOGY

The concept of PEIS-Ecology, originally introduced by Saffiotti and Broxvall [18], puts together insights from the fields of ambient intelligence and autonomous robotics to generate a radically new approach toward the inclusion of robotic technologies in everyday environments. In this approach, advanced robotic functionalities are not achieved through the development of extremely advanced robots, but through the cooperation of many simple robotic components. The concept of PEIS-Ecology builds upon the following ingredients.

First, any robot in the environment is abstracted by the *uniform notion* of PEIS (Physically Embedded Intelligent System). The term "robot" is taken here in its most general interpretation: a computerized system interacting with the environment through sensors and/or actuators. A PEIS can be as simple as a toaster or as complex as a humanoid robot.

[1] PEIS is pronounced /peɪs/ like in 'pace'.

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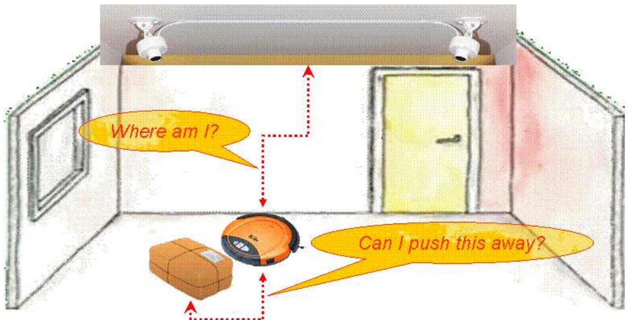

Fig. 1. A simple example of PEIS-Ecology.

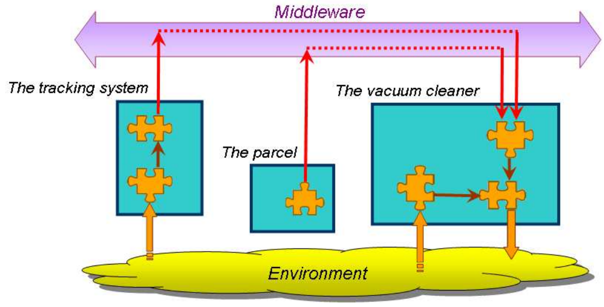

Fig. 2. Functional view of the same PEIS-Ecology.

In general, we define a PEIS to be a set of inter-connected software *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 PEIS or in other PEIS.

Second, all PEIS are connected by a *uniform communication model*, which allows the exchange of information among the individual PEIS-components, while hiding the heterogeneity between PEIS and in the physical communication layers. We use a distributed communication model combining a tuple-space with an event mechanism (see section V-A below).

Third, all PEIS in an ecology can cooperate by 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 complement its own.

As an illustration of these concepts, consider an autonomous vacuum cleaner in a home. (See Figure 1.) By itself, this simple PEIS 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 navigation component of the cleaning robot, which can thus realize smarter cleaning strategies. Suppose further that the cleaner encounters an unexpected parcel on the floor. It could push it away and clean under it, but to decide this its navigation component needs to know the weight of the parcel. If the parcel is equipped with an IC-tag, it can act as a PEIS and communicate this information directly to the cleaner.

We define a PEIS-*Ecology* to be a collection of inter-connected PEIS, all embedded in the same physical environment. We call *configuration* of a PEIS-Ecology the set of connections between components within and across the PEIS in the ecology. Figure 2 shows the configuration of the above ecology. Note that all the connections between PEIS are mediated by a shared middleware (see section V-A below). Importantly, the same ecology can be configured in many different ways depending on the context — e.g., depending on the current task, the environmental situation, and available resources. In our example, if the cleaner exits the field of view of the cameras, then the ecology may be reconfigured to let the cleaner use its own odometric component for localization.

Similarly to a natural ecosystems, a PEIS-Ecology is characterized by: (i) the relationship between living entities (PEIS) and the environment (through sensors and actuators), (ii) the relationship among these entities (through the cooperation model), and (iii) the notion that complex behavior emerges from the interaction of simpler units. Moreover, a PEIS-Ecology is intended to be heterogeneous, that is, to include different *species* of entities in symbiotic interaction. In the PEIS-Ecology vision, humans can constitute one of the species who participate in the ecology, and interact with the other PEIS in it.

III. POTENTIALS OF PEIS-ECOLOGY

A PEIS-Ecology redefines the very notion of a *robot* to encompass the entire environment: a PEIS-Ecology may be seen as a "cognitive robotic environment", in which perception, actuation, memory, and processing are pervasively distributed in the environment. The complex functionalities of this environment are not determined in a centralized way, but they emerge from the co-operation of many simpler, specialized, ubiquitous PEIS devices. The number and capabilities of these devices do not need to be known *a priori*: new PEIS can join or leave the ecology at any moment, and their existence should be automatically detected by the other PEIS.

The PEIS-Ecology approach simplifies many of the difficult problems of current autonomous robotics by replacing complex on-board functionalities with simple off-board functionalities plus communication. In the example above, the global localization of the robot is easily achieved by the static cameras; and the best way to access the properties of the parcel is to store those properties in the parcel itself.

As a more complex example, consider a mobile robot who should monitor a house using an electronic nose (e-nose), e.g., to detect food that has gone bad, gas leakages, or other problems. The robot would have to detect anomalous odors, navigate to the source, and classify the odor. This solution is not possible today due the current limitations of mobile olfaction: the e-nose must be placed near the odor source in order to classify it, but locating the source by following the odor plume is still an unsolved problem. Moreover, odor classification can only be done reliably if the number of possible classes is small. The PEIS-Ecology solution to this problem would be as follows. We assume that the environment contains a number of very simple, cheap and small e-noses placed at critical locations, e.g., inside the refrigerator or near the cooker. These simple devices can detect an abnormal gas concentration, but they are unable to classify the type of odor. We also assume that objects in the environment (e.g., goods in the refrigerator) can have RFID tags attached, which contain information about the object itself. When a simple e-nose detects an alarm, its location is sent to a mobile robot equipped with a sophisticated (and expensive) e-nose. The robot navigates to that place, and smells the different objects there. The information stored in the object's tags is communicated to the robot, and it provides a context to restrict the classification problem. This solution has been explored and experimentally validated in [14].

In addition to simplifying problems that are difficult to address using a traditional approach, the PEIS-Ecology approach can bring a number of pragmatic benefits. A PEIS-Ecology is intrinsically flexible and customizable. End-users would only install those robotic devices which are useful for their specific problems, and possibly add/remove/replace devices later on to accommodate different needs. This also allows incremental and piece-wise deployment. The end-users only need to buy robotic components as needed, e.g., starting with just a simple robotic vacuum cleaner and ending with a completely robotized intelligent home. This will likely make a PEIS-Ecology more easily acceptable and affordable. (Compare this with the alternative to buy a hypothetical all-mighty robotic assistant at once.) From the point of view of the producers, it is probably easier to invest in the production of (and to create a market for) enhanced familiar components with a well defined purpose and functionality.

The PEIS-Ecology approach also recognizes the fact that our environments are increasingly populated by embedded devices and tagged objects. For instance, Wal-Mart already requires that all commercial goods are equipped with an RFID tag. These tags can carry a large amount of information about the objects in the environment. In future, they may also be writable or they may be able to transmit some sensor-based information. We claim that a robot should exploit the richness of this environment rather than operate in isolation from it.

IV. CHALLENGES OF PEIS-ECOLOGY

The above discussion might give the impression that the PEIS-Ecology approach would allow us to use robotic components to solve complex tasks by simply using state-of-the-art technology, connected and combined "in the right way". This is only partly true. The PEIS-Ecology approach presents us with a number of new, interesting research challenges that need to be solved before this approach can be exploited to its full potential.

A. Heterogeneity

A PEIS-Ecology may include highly heterogeneous devices, which rely on different hardware and software platforms and different communication media. Heterogeneity may also arise from the different levels at which the devices need to exchange information: from raw data streams to one-shot data readings to symbolic communication.

In face of this, a PEIS-Ecology should provide the means to establish a meaningful communication between different PEIS. Physical diversity should be abstracted, and contents should make reference to a common ontology and measurement system. Achieving this requires a suitable middleware, and the establishment of a suitable shared ontology. Both problems are open research issues.

B. Integrating the physical and the digital world

In a classical robotic system, the robot's interaction with the environment and its objects is physically mediated: properties of the objects are estimated using sensors, and their state can be modified using actuators. In a PEIS-Ecology, a robot (PEIS) can interact with an object (another PEIS) both physically and digitally: the robot can directly query properties from the object, and it can ask it to perform an action. How to coordinate and integrate these two forms of interaction is a new research problem. Suppose for instance that the robot is now seeing a closed door in front of it. How can the robot know that, in order to open that door, it has to send the `open` request to the PEIS with ID = 301?

C. Self-configuration

Perhaps the strongest added value of a PEIS-Ecology comes from its ability to integrate the functionalities available in the different PEIS in a configuration, and to automatically create and modify this configuration depending on the current context. Here, the relevant contextual conditions include the current task(s), the state of the environment, and the resources available in the ecology. Self-configuration is the key to flexibility, adaptability and robustness of the system — in one word, to its *autonomy*. Although much work has been done in several fields on the principles of self-configuration (e.g., ambient intelligence [9], web service composition [17], distributed middleware [3], autonomic computing [20]), no satisfactory solution exists.

An essential requirement for self-configuration is that the PEIS-Ecology, considered at the system level, should have the capability to *reflect* on its own status. In particular, each PEIS should be aware of all the other PEIS present in the ecology, of the functionalities that they can provide, and of their current availability. In the scenario in Figure 1, the PEIS-Ecology should know that there is a camera system able to track the cleaner in order to decide to connect that system to the cleaner. As we shall discuss below, this may require more than syntactic matching of functionality templates.

D. Self-adaptation

A PEIS-Ecology system should dynamically adjust its configuration to adapt to a changing environments and new situations. It should exploit new opportunities and compensate for functionalities which are no longer available (*self-repair*).

It should also update its internal models (knowledge) in order to adapt to long-term changes, e.g., to smoothly adapt to a human user who is growing older. None of these problems has a state of the art solution today.

E. The human dimension

A PEIS-Ecology is meant to operate in the presence of, and in the service of, humans. It is therefore essential that the development of a PEIS-Ecology takes into careful consideration the place of the humans in it. Three issues are especially important in this context.

Interface. The way the PEIS-Ecology interfaces with the human inhabitants is critical to its usability and acceptability. The human should perceive the PEIS-Ecology as one entity, and experience a full and natural interaction, including compliance with social rules.

Safety. The system should not put at risk the physical and psychological safety of the humans, including their privacy. Ideally, we would like to prove invariant properties and safety constraints of a PEIS-Ecology, but the formal analysis of the emergent properties of a self-organizing system is a totally open problem.

Symbiosis. A PEIS-Ecology should be able to incorporate humans as one of its parts, and to operate in symbiosis with them. It should be able to infer the status and intentions of the human from observations, and adapt its behavior to that. For instance, if a human shows the intention to relax, the vacuum cleaner should move to a different room.

V. PROGRESS TOWARD A PEIS-ECOLOGY

All the above challenges involve hard, long-term research problems, and even relatively small steps are crucial to the realization of the PEIS-Ecology vision. In this section, we hint at the partial solutions to these challenges that we have developed in the first 2.5 years of our project. Full technical details can be found in the referenced papers.

A. Heterogeneity

Our realization of the PEIS-Ecology approach handles heterogeneity by means of a middleware called the PEIS-kernel [2]. This provides uniform communication primitives, and performs services like network discovery and routing of messages between PEIS. A first open-source version of the PEIS-kernel has been delivered in 2006 under a set of GNU licenses, and it is available from the project website.

The PEIS-kernel implements a communication model based on a distributed tuple-space, endowed with the usual `insert` and `read` operations. In addition, it provides event-based primitives `subscribe` and `unsubscribe`, by which a PEIS-component can signal its interest in a given key. When an insert operation is performed, all subscribers are notified. Subscription, notification, and distribution of tuples are managed by the PEIS-kernel in a way which is transparent to the PEIS-component. Hybrid tuple/events approaches of this type are increasingly used in ubiquitous computing and in ambient intelligence [1], [19].

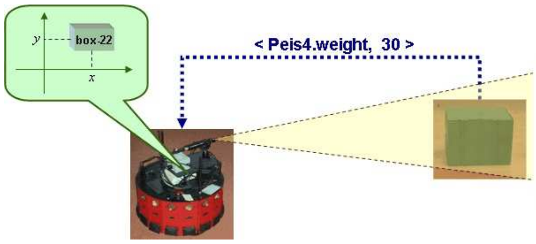

Fig. 3. In a PEIS-Ecology, a robot may acquire information about an object both by perception and by digital communication.

The PEIS-kernel can cope with the fact that PEIS may dynamically join and leave the ecology. At any moment, each PEIS-component can detect the presence of other components and trade with them the use of functionalities. For instance, if the navigation component in the cleaner in Figure 2 above requires a localization functionality, it simply looks for a tuple announcing a *compatible* functionality in any PEIS-component: if one is found, then that component is booked and a subscription to it is created. Compatibility is decided using a shared PEIS-Ontology.

B. Integrating the physical and the digital world

Our approach to cope with this challenge is based on an extension of the concept of perceptual *anchoring* [4]. Anchoring is the process of connecting, inside an intelligent system, the symbols used to denote an object (e.g., `box-22`) and the percepts originating from the same objects (e.g., a green blob in the camera image).

In a PEIS-Ecology, anchoring must connect the perceptually acquired information about the properties of an object, and the information about that object which is provided by the object itself. Consider for instance the situation shown in Figure 3. The robot is seeing a green PEIS-box, which it has internally labeled as `box-22`. How can the robot decide that, in order to know the weight of that box it has to read the `weight` property from the PEIS with ID = `Peis4`? The same problem arises on the action side of coordination.

We use a mechanism similar to the Find primitive of the anchoring framework [4]. The robot queries the tuple-space for all `PhysicalRepresentation` tuples of each PEIS in the ecology (each PEIS publishes this tuple). It then tries to match these tuples to the perceived properties of the parcel in front of it, e.g., being box-shaped, green, and of a given size. In

Fig. 4. A robot querying and then pushing a PEIS-box.

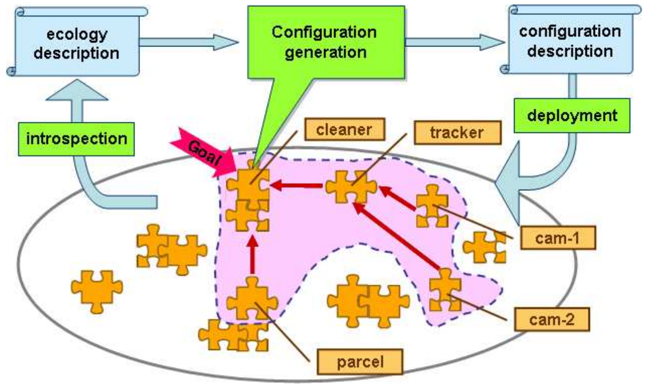

Fig. 5. Self-configuration of a PEIS-Ecology.

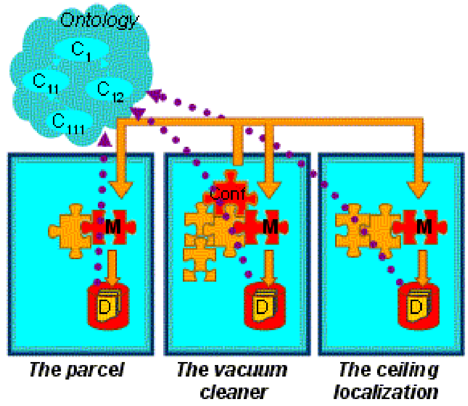

Fig. 6. Outline of our self-configuration framework.

our example, the matching succeeds for `Peis4`. Once this is done, the robot can ask additional properties to `Peis4` (e.g., its weight) and combine these properties with the observed ones. Figure 4 shows two snapshots from the execution of this task during a project demonstration, in which the robot decides to push the parcel out of the way. The full experiment is reported in [2].

In general, both perceptual and symbolic information about the same object coming from several PEIS can be matched and combined in the way above. This mechanism is explored in greater detailed in [11].

C. Self-configuration

One of the strongest tenets of the PEIS-Ecology approach is the fact that the task and the configuration are not pre-defined: the ecology should be able to dynamically self-configure in order to adapt to the current task and the current situation.

Figure 5 illustrates the self-configuration problem in a PEIS-Ecology. The self-configuration process can be initiated by any PEIS whenever it needs to perform a task that may benefit from the help of other PEIS. In the example in the figure, this PEIS is a vacuum cleaner. In general, the configuration process operates in three phases: assess the current state of the ecology (introspection), e.g., which functionalities are available and where; generate a suitable configuration for the target task; and instantiate this configuration on the ecology by setting the needed parameters and establishing the needed subscriptions.

How to realize a self-configuration process of this type is a hard open problem for autonomous systems in general, and for distributed robotic systems in particular. In a PEIS-Ecology, this problem is exacerbated by the fact that a PEIS-Ecology is intrinsically dynamic (PEIS may join and leave the ecology at any time) and highly heterogeneous. Our current approach to deal with these difficulties is based on the following ingredients:

- An *advertising mechanism* that allows any PEIS to dynamically join the ecology and let all the other PEIS know about the functionalities it can provide.
- A *discovery mechanism* that allows each PEIS to find which other PEIS can provide a functionality compatible with its needs.
- A *configuration mechanism* able to create a configuration for a given task by composing functionalities from different PEIS.
- A *monitoring mechanism* able to change the configuration if these functionalities become unavailable.

The above mechanisms help to cope with the dynamic aspect. To help coping with the heterogeneity aspect, we also need an *ontology*, which allows us to describe the functionalities provided by each PEIS in the ecology and the data on which they operate, and to define the notion of compatibility used by the discovery mechanism.

Figure 6 illustrates our approach. Every PEIS is provided with a local directory of descriptions `D` and with a special component `M` that can access the descriptions and advertise them to the rest of the ecology. Some PEIS can be equipped with a special *configurator* component, denoted by `Conf`, that is capable of retrieving the descriptions and computing a meaningful configuration based upon the information stored in them. The configurator also takes care of deploying and monitoring the generated configuration. For the monitoring part, the configurator subscribes to `fail` signals from the connected PEIS, and re-triggers the configuration algorithm if any PEIS drops from the configuration for any reason. Note that not all PEIS need to include a configurator, and that multiple configurator components can exist in the ecology. Whenever a PEIS needs to generate a configuration, it asks the service of an available configurator component.

The configurator component can be implemented using different approaches. In our project, we are exploring two complementary approaches for that. The first is a *plan-based*, centralized approach [15]. In this approach, we use a global hierarchical planner to generate the (minimum cost) configuration for a given task. The second is a *reactive*, distributed approach [7]. In this approach, the configurator creates a partial configuration, and assumes that the connected PEIS are able to recursively extend this configuration if needed. If they

Fig. 7. Two views of the PEIS-Ecology testbed.

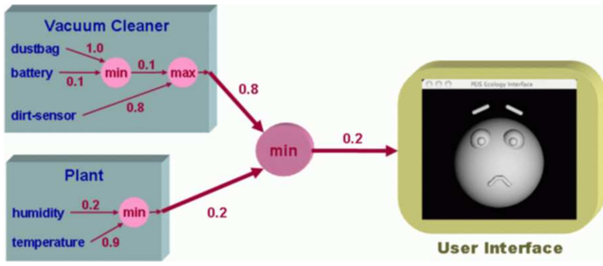

Fig. 8. Computing and displaying the state of a PEIS-Ecology. Numbers indicate degrees of satisfaction.

are not, the configurator receives a `fail` signal and tries a different local configuration.

The two approaches have the typical complementary strengths and weaknesses of plan-based and reactive approaches. The plan-based approach is guaranteed to find the optimal configuration if it exists, but it cannot easily cope with changes in the ecology. The reactive approach can quickly adapt to changes in the state of the ecology, but it might generate non-optimal configurations and it might fail to find a configuration even if one exists. Eventually, we hope to be able to combine these two approaches into a hybrid configurator.

D. Self-adaptation

Self-adaptation has been left as a future issue in our current development. Some form of self-repair is provided as a by-product of the above approach to self-configuration: if a PEIS signals that a functionality used in the current configuration is not available any more, the configurator component tries to generate an alternative configuration. This simple solution needs to be extended to cover more interesting cases, like one in which a PEIS fails silently, or one in which the cost of a functionality changes in a way to make another configuration preferable. In general, an important part of the short-term adaptation problem is how to determine when the current configuration should be changed.

E. The human dimension

In order to validate the utility and acceptability of a PEIS-Ecology for humans, we have built a physical testbed facility, called the PEIS-Home, which looks like a typical Swedish bachelor apartment (Figure 7). The PEIS-Home is equipped with a communication infrastructure and with a number of PEIS, including: static cameras, mobile robots, sensor nodes, a refrigerator equipped with gas sensors and an RFID reader, and many more.

We have also developed a first solution to the problem of interfacing a PEIS-Ecology with a human, based on two new concepts [8]. First, the concept of *common interface point*, which collects and summarizes the relevant information about the status of the PEIS-Ecology, making sure that the user perceives this ecology as one system. Second, the concept of *expression-based semantics*, which provides a uniform way to represent the status of each PEIS in the ecology by a degree of satisfaction, and to convey this information to the user by a human-understandable expression. These concepts are illustrated in Figure 8, in a case in which a plant PEIS (with humidity and temperature sensors) needs watering.

F. Experimental validation

The PEIS-Ecology project follows a methodology which is strongly experimental: principles and techniques are systematically evaluated on experimental platforms, and the results are used to refine these principles and techniques.

We have run a large number of experiments using the PEIS-Home testbed In these first 2.5 year of this project. These include experiments that reproduce the push-box scenario mentioned in the Introduction [2], as well as experiments that reproduce the olfaction scenario discussed in section III . That last series in particular has validated the hypothesis that the PEIS-Ecology approach allows us to address problems like mobile olfaction that are beyond the current capabilities of stand-alone autonomous robots [14].

VI. CONCLUSIONS

The integration of robots and smart environments is believed by many to be the key factor that will enable the massive inclusion of robotic technologies and products into our everyday life. A few projects were recently started with the aim to explore the scientific, technological and practical implications of this integration. Currently the largest efforts are probably the Network Robot Forum [16], the U-RT project at AIST [13], and the Korean Ubiquitous Robot Companion program [10]. The PEIS-Ecology project presented in this paper is part of the latter effort. The PEIS-Ecology project is distinct in its strong emphasis on the study of the fundamental scientific principles that underly the design and operation of an ubiquitous robotic system.

In this paper, we have discussed the innovation potential of the PEIS-Ecology approach, the main scientific challenges that it entails, and the first solutions that have been developed in the framework of the PEIS-Ecology project. We believe that these challenges, as well as the solutions that we are developing with our project, are not limited to a PEIS-Ecology but also apply to any ubiquitous robotic system.

The progress of the PEIS-Ecology project has been very intense, and we are extremely pleased with the results obtained in these first 2.5 years of activity. The next steps of the project include: the continued investigation of the scientific issues discussed in this paper, with special emphasis on the issues of ontology, dynamic reconfiguration, and human inclusion; and the practical exploration of the applicability of the concepts and tools developed in this project to concrete home scenarios.

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