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Steps Toward an Ecology of Physically Embedded Intelligent Systems

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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. In this paper we introduce this concept, 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. The discussion in this paper is also relevant to any type of ubiquitous robot or network robotic system.

1 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 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 offers a new paradigm to develop pervasive robotic applications. This paradigm 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. However, the development of PEIS-Ecology entails a number of new research challenges that need to be solved before this potential can be fully exploited. The purpose of this paper is to discuss these challenges, and to present some initial solutions that have been developed in the context of a collaborative project between Sweden and Korea.

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 5 we summarize the current progress in our realization of a PEIS-Ecology. In the interest of space, we do not give 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 `aass.oru.se/~peis/`.

2 The Concept of PEIS-Ecology

The concept of PEIS-Ecology, originally introduced by Saffiotti and Broxvall [15], 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.

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

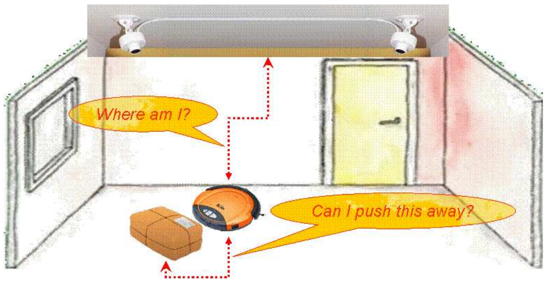

Figure 1: A simple example of PEIS-Ecology.

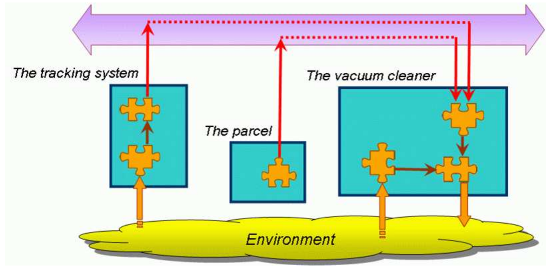

Figure 2: Functional view of the same PEIS-Ecology.

A PEIS can be as simple as a toaster or as complex as a humanoid robot. 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 5.1 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 compensate or 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. Importantly, the same ecology can be configured in many different ways depending on the context — e.g., the current task, situation, and resources. In our example, if the cleaner exits the field of view of the camera the ecology may be reconfigured to let the cleaner use its own odometry component for localization.

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.

Like in 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.

3 Potentials of PEIS-Ecology

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 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 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 e-nose. The robot navigates to that place, and smells the different objects there. The information stored in the object's tags provides a context to restrict the classification problem. This solution has been explored and experimentally validated in [10].

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) 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.

4 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, 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.

4.1 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 ontology. Both problems are open research issues.

4.2 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 (PEIS) both physically and digitally: the robot can directly query properties from the object, and it can ask it to perform an action. How those two forms of interaction should be coordinated and integrated is a new research problem. For instance, suppose that a robot is seeing a closed door in front of it. How can it know that in order to open that door, it has to send the `open` command to the PEIS with ID = 301?

4.3 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. 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 [8], web service composition [14], distributed middleware [3], autonomic computing [17]), no satisfactory solution exists. An additional challenge is that the PEIS-Ecology should have the capability to *reflect* on its own status, e.g., being aware of the functionalities and current availability of each PEIS in it. 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.

4.4 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.

4.5 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.

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

5 Progress Toward a PEIS-Ecology

All the above challenges involve hard, long-term research problems, and even relatively small steps are likely to be beneficial 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 two years of our project. Full details can be found in the referenced papers.

5.1 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.

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, 16].

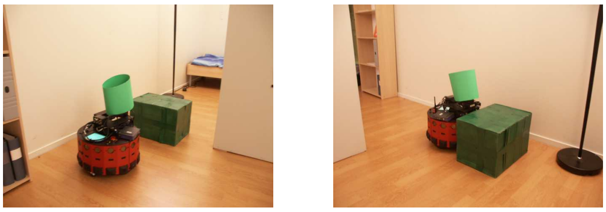

Figure 3: A robot querying and then pushing a PEIS-box.

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.

5.2 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 the case in Figure 1. The robot sees a parcel in front of it; it also finds from the PEIS-Ecology tuple-space that there is a PEIS, among others, which is called PEIS-22. How does it know that these two are the same object?

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. The matching succeeds for PEIS-22. Once this is done, the robot can ask additional properties to PEIS-22 (e.g., its weight) and combine these properties with the observed ones. In general, both perceptual and symbolic information about the same object coming from several PEIS can be matched and combined in this way.

Figure 3 shows two snapshots from the execution of this task during an actual experiment, in which the robot decides to push the parcel out of the way. The full experiment is reported in [2].

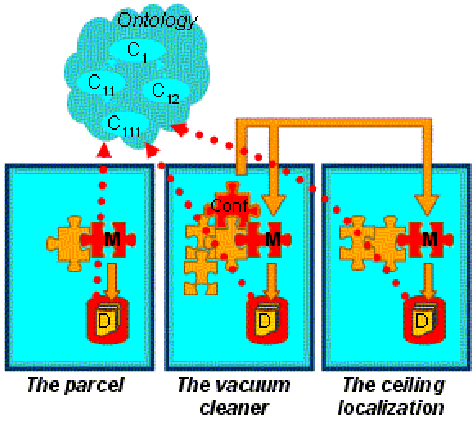

Figure 4: The self-configuration framework.

5.3 Self-configuration

The problem of self-configuration 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 self-configuration is based on the following ingredients:

- An *ontology* that allows us to describe the functionalities provided by each PEIS in the ecology and the data on which they operate; the ontology helps to cope with the heterogeneity aspect.
- An *advertising mechanism* that allows each PEIS to dynamically join the ecology and let every PEIS know about the functionalities it can provide; this mechanism helps to cope with the dynamic aspect.
- A *discovery mechanism* that allows each PEIS to find which other PEIS can provide a functionality compatible with its needs, given the above ontology.
- A *configuration mechanism* able to create a configuration for a given task by composing functionalities from different PEIS, and to change the configuration if these functionalities become unavailable.

Figure 4 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 propagate them to the rest of the ecology. Any 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. Multiple configurator components can exist in the ecology. Both the component descriptions and the configurator components have access to the same common ontology.

Figure 5: Two views of the PEIS-Ecology testbed.

The configurator component can be implemented using different approaches. One possibility that we have explored is the use of a *plan-based* approach, in which a global hierarchical planner generates the (minimum cost) configuration for a given task [11]. This approach has the typical strength and weakness of any plan-based approach: it is guaranteed to find the optimal configuration if it exists, but it cannot easily cope with changes in the ecology. We are currently investigating a complementary *reactive* approach. In this approach, the configurator creates a local configuration, and assumes that the connected PEIS are able to do the same if needed. The configurator then subscribes to `fail` signals from the connected PEIS, and re-triggers the configuration algorithm if any PEIS drops from the configuration for any reason.

5.4 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 reactive approach to self-configuration mentioned above: 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 [13].

5.5 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 5). The PEIS-Home is equipped with a communication infrastructure and with a number of PEIS, including static cameras, mobile robots, a refrigerator equipped with gas sensors and an RFID reader, and many others.

We have run several experiments in this testbed, including one reproducing the olfaction scenario discussed in section 3 above. That experiment has validated the hypothesis that we can by-pass some of the difficult prob-

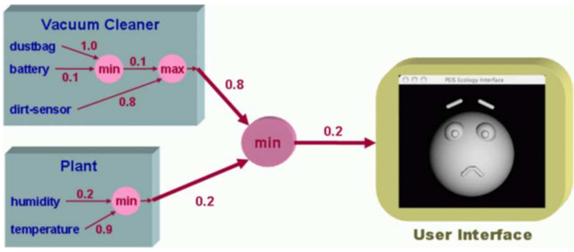

Figure 6: Computing and displaying the state of a PEIS-Ecology. Numbers indicate degrees of satisfaction.

lems of mobile olfaction by embedding the robot in a PEIS-Ecology [10].

We have also developed a first solution to the problem of interfacing a PEIS-Ecology with a human, based on two new concepts [7]. 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 6, in a case in which a plant PEIS (with humidity and temperature sensors) needs watering.

6 Conclusions

The idea of integrating robots and smart environments is starting to pop up at several places and under several names, including network robot systems [12], sensor-actuator networks [5], and ubiquitous robotics [9]. To the best of our knowledge, however, there are only two concrete major efforts today that try to put this vision into practice: the Japanese Network Robot Forum (NRF) [12]; and the Korean Ubiquitous Robot Companion program (URC). The PEIS-Ecology approach discussed in this paper is part of the latter effort.

In this paper, we have discussed the strong potential of the PEIS-Ecology approach, as well as the main research challenges that it entails. We believe that these challenges, as well as the solutions that we have proposed, are not limited to a PEIS-Ecology, but also apply to the other approaches mentioned above.

Acknowledgments

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