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The Concept of Peis-Ecology: Integrating Robots in Smart Environments

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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. In this note I introduce this concept, summarize its main technological aspects, and speculate on its potential impact for space exploration.

1 Introduction

Autonomous robotic devices are vital to the performance of space missions. These range from smart servo-controlled devices (e.g., an antenna or a camera) to autonomous mobile robots (e.g., planetary rovers) and to future interactive astronaut assistants. Each robotic device operates in its specific environment, which is usually not fully predictable and not fully observable, and which may include humans. In the classical view of autonomous robotics, the robot and its environment are seen as two distinct entities. This view is often assimilated to a two-player antagonistic game, in which the robot has to find a strategy to achieve its goals in spite of the actions performed by the environment.

The "Peis-Ecology" approach to autonomous robotics takes an ecological view of the robot-environment relationship, in which the robot and the environment are seen as parts of the same system, engaged in a symbiotic relationship toward the achievement of a common goal, or equilibrium status. We assume that robotic devices (or Peis, for "Physically Embedded Intelligent Systems") are pervasively distributed throughout the working space in the form of sensors, actuators, smart appliances, RFID-tagged objects, or more traditional mobile robots; and that these Peis can communicate and collaborate with each-other by providing information and by performing actions. Humans can also be included in this approach as another species of Peis inside the same ecosystem.

The Peis-Ecology approach was developed in the context of a collaborative research project between Sweden and Korea between 2004 and 2008. The target application of this approach was everyday domestic assistance, especially (but not only) to elderly people. However, this approach can in principle be applied to other domains, both indoor and outdoor, including space exploration. In this note, we outline the concept of Peis-Ecology, discuss the major scientific and technological challenges entailed by its realization, and show the results achieved in the course of our development with respect to these challenges. We also discuss the expected developments of the Peis-Ecology approach in the near future, and speculate on the applicability and benefits of this approach in the context of space exploration.

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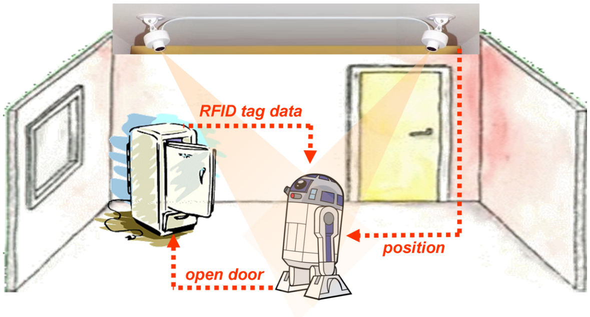

FIGURE 1. *A simple example of* PEIS-*Ecology.*

2 Current Status

The PEIS-Ecology project was started in October 2004 as a collaborative effort between Sweden (the AASS Mobile Robotics Lab at the University of Örebro) and Korea (the Electronic and Telecommunication Research Institute). Currently this project has attracted additional funding from the Swedish Research Council and from the Swedish National Graduate School in Computer Science, and it has grown to an effort of about 80 person-month per year. In this section, we briefly recall the main concept underlying this project, and summarize the main scientific and technological achievements in the first 40 months of this project.

2.1 The Concept of PEIS-Ecology

The concept of PEIS-Ecology, originally introduced by Saffiotti and Broxvall [15], builds upon the following ingredients:

First, any robot in the environment is abstracted by the *uniform notion* of PEIS[1] (Physically Embedded Intelligent System). The term "robot" is taken here in its most general interpretation: any device incorporating some computational and communication resources, and able to interact with the environment via sensors and/or actuators. 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 can be connected to sensors and actuators in that physical entity, as well as 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 of the PEIS and of the physical communication layers. In practice, we use a distributed communication model that combines a tuple-space with an event mechanism.

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 to complement its own. Functionalities here are meant to be modules that produce and consume information, and may interact with the physical environment by means of sensors and actuators. Typically, functionalities are in one-to-one correspondence to the software components in a PEIS.

Finally, we define a PEIS-Ecology to be a collection of inter-connected PEIS, all embedded in the same physical environment.

As an illustration of these concepts, consider a home robot with the task of grasping a milk bottle from the fridge. (See Figure 1.) In a classical approach, the robot would use its sensors to acquire information from the environment — e.g., to self-localize, and to acquire the relevant parameters of the fridge handle and of the milk bottle. It would then use its actuators to manipulate the environment — e.g., to open the fridge door and to grasp the milk bottle. In a PEIS-Ecology, by contrast, the robot would ask (some of) the needed information from the environment — e.g., it would get its position from cameras in the ceiling; and it would get the shape, weight, and grasping points of the milk bottle from the bottle itself, equipped with a mote or an RFID tag. It would also ask the environment to perform (some of) the needed actions — e.g., it would ask the fridge to open its door.

Given a PEIS-Ecology, we call a set of connections between components within and across the ecology a *configuration* of that PEIS-Ecology. 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 the above example, if the robot exits the field of view of the ceiling cameras, then the ecology may be reconfigured to let it use another PEIS in the ecology for localization, e.g., a camera on the fridge or the robot's own odometric system.

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 per-

[1]PEIS is pronounced /peIs/ like in "pace".

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vasively distributed in the environment. The complex functionalities of this environment are not determined in a centralized way, but they emerge from the cooperation 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 and capabilities 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 milk 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 milk box is to store those properties in the box itself. The Peis-Ecology approach can also help us to address problems which are beyond the capabilities of current robotic systems. An example of this type is reported in [1], where a Peis-Ecology is used to solve a home monitoring task involving the use of olfaction, which would be hard to solve otherwise due the current limitations of mobile olfaction.

The Peis-Ecology approach can also bring a number of pragmatic benefits. A Peis-Ecology is intrinsically modular, flexible and customizable. Users would only need to acquire new robotic components as needed, e.g., starting with just a simple robotic vacuum cleaner and adding new Peis devices according to their changing needs and desires. Thus, the Peis-Ecology approach is likely to provide an affordable and acceptable road to include robotic technologies in everyday environments. Since each new Peis can combine its functionalities with those of the already existing ones, the value of the whole Peis-Ecology can increase more than linearly with its cost.

In spite of the above attractive benefits, 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 next three subsections outline three of the most peculiar ones, together with our progress in addressing them.

2.2 Dealing with Heterogeneity

The first fundamental challenge is 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 oneshot 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.

In our work, we have developed an open-source middleware called the Peis-kernel [2]. This provides uniform communication primitives, and performs services like network discovery and routing of messages between Peis on a P2P network. The Peis-kernel also 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 tuple 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.

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 robot in Figure 1 above requires a localization functionality, it simply looks for a tuple announcing a *compatible* functionality in any Peis-component: if one is found, that component is booked and a subscription to it is created. Compatibility is decided using a shared Peis-Ontology.

The Peis-Ecology middleware has been released as open-source under a set of GNU licenses, and it is available from the project website [14].

2.3 Integrating the physical and the digital world

The second fundamental challenge of a Peis-Ecology can be described as follows. 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. The new challenge here is how to coordinate and

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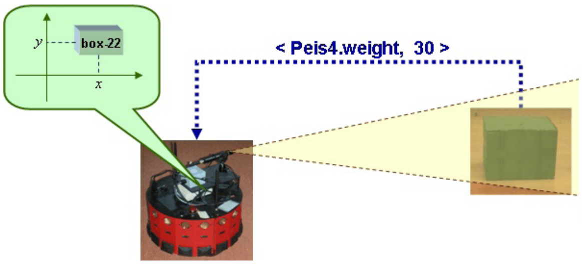

Figure 2. *Linking perceptual information and digital information in a* Peis*-Ecology.*

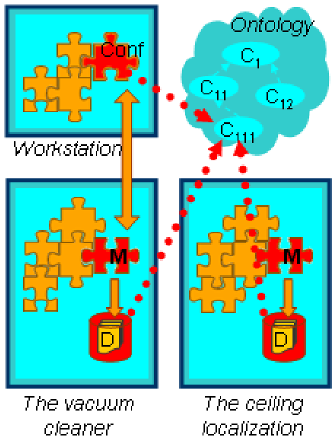

Figure 3. *Outline of our self-configuration framework.*

integrate these two forms of interaction.

Consider a robot in a Peis-Ecology, which is facing a closed door. The robot would need to know if this door can be opened. Suppose that the robot is aware, through the advertisement mechanism mentioned above, that there is a Peis in the Peis-Ecology, with ID = `Peis301`, which offers the action 'open'. If the robot can establish that the door which it is perceiving in front of it is the same physical object as `Peis301`, then the robot will know that that door can perform the action of opening, by linking the (digital) action 'open' of `Peis301` with the (physical) action of opening the specific door. It will also know that in order to open that specific door it needs to send the request `<open>` to the Peis with ID = `Peis301`. A similar linkage would allow the robot to augment its perceptual knowledge about an object by using the properties communicated by the corresponding Peis.

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). More specifically, the robot queries the tuple-space for all `PhysicalRepresentation` tuples of each Peis in the ecology (each Peis must publish this tuple by convention). It then tries to match these tuples to the perceived properties of the object in front of it, e.g., being box-shaped, green, and of a certain size. If the matching succeeds for a given Peis, say the one with ID = `Peis4`, then the robot can ask additional properties to `Peis4` (e.g., its weight) and combine these properties with the observed ones, e.g., to decide if the box can be pushed.

2.4 Self-configuration

Perhaps the strongest added value of a Peis-Ecology comes from the ability to integrate the functionalities available in the different Peis according to a given 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*.

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 highly heterogeneous and intrinsically dynamic.

Our current approach to self-configuration is partly inspired by work in the field of web service composition [7]. It 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.

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- 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 in a uniform way 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 3 illustrates our approach, in the case of a simple ecology consisting of a vacuum cleaner, a ceiling camera tracking system, and a workstation. 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 to perform a task, it asks the service of an available configurator component.

The configurator component can be implemented using different approaches. In our project, we explore two complementary approaches for that. The first approach is a *plan-based*, centralized approach [11, 12]. 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 local configuration, and assumes that the connected PEIS are able to recursively extend this configuration if needed. If they are not, the configurator receives a `fail` signal and tries a different local configuration. Both approaches provide some simple form of self-repair: if a PEIS signals that a functionality used in the current configuration is not available any more, the configurator tries to generate an alternative 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 has problems to scale up and it cannot easily cope with changes in the ecology. The reactive approach scales up smoothly and it 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.

2.5 Experimental Validation

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

In order to follow this methodology, we have built a physical testbed facility called the PEIS-Home. This facility looks like a typical Swedish bachelor apartment (Figure 4). The PEIS-Home is equipped with a communication infrastructure and with a number of PEIS, including static cameras, mobile robots, multi-media devices, sensor nodes (motes), a refrigerator equipped with gas sensors and an RFID reader, and many more.

We have used this testbed to run a large number of experiments, with several aims: to test our technical solution and measure our progress; to validate the effectiveness of the developed techniques; to evaluate the acceptability of the PEIS-Ecology concept to human users, with special attention to elderly people; and to demonstrate the PEIS-Ecology concept to the society at large. Descriptions and videos of some of the experiments can be found on the PEIS-Ecology home page [14].

3 Future Directions

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 take into careful consideration the place of the humans in it.

The way in which a PEIS-Ecology interfaces with the human inhabitants is critical to its usability and acceptability. Humans should perceive the PEIS-Ecology either as one entity, or as a set of individual PEIS, depending on the context. In either case, they should use similar interaction modalities, and experience a natural interaction in compliance with social rules. The humans should also be made aware of what the PEIS-Ecology can afford to them, with special emphasis on those affordances which are most relevant given the current context.

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Figure 4. *Two views of the* Peis*-Home experimental testbed. Left: the kitchen, with a nose-equipped robot inspecting a smart fridge. Middle: the living room, with a human-interface robot in its parking position. Right: A Mote-IV mote monitoring temperature and humidity of a plant.*

In the reverse direction, a Peis-Ecology should be able to incorporate humans among its parts, and to operate in symbiosis with them [5]. It should be able to infer the status and intentions of humans 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. A Peis-Ecology should also be able to infer what the humans can afford to it: for instance, the vacuum cleaner could ask the human to empty its dust-bag if it knows that the human can afford that. Ideally, it should also be able to smoothly update its model of what a human user can afford to adapt to changes in this user, e.g., growing older.

Work more directly concerned with the inclusion of humans into a Peis-Ecology has just started at the time of this writing, and it is expected to be a major drive of future developments in this area. Our approach is to see humans as just another species of Peis in the ecology, which may use the (perceptual, acting, or information processing) functionalities provided by the rest of the Peis-Ecology, and may provide functionalities to it. What makes humans a peculiar type of Peis is that their goals and desires have a high priority status, and that they need to use dedicated human interface components to communicate with the rest of the ecology. Currently, we are exploring the use of template-based interface components to select, and make visible to the users, the capabilities of the Peis-Ecology which are relevant in the current context [3]. For instance, when a human sits on the sofa after dinner, the options of bringing a drink, bringing the phone, or playing music, are made available to her. When the same human leaves the house, the options of patrolling the house or keeping the house warm are offered instead.

4 Potential for Space Exploration

The concept of Peis-Ecology was originally developed to allow the inclusion of robotic technologies in our homes, in order to improve the quality of life, safety and independence of citizens in general, and senior citizens in particular. Despite this, the Peis-Ecology concept has several characteristic that makes it a promising approach to the inclusion of robot technologies in space exploration.

Thanks to its modularity, self-configurability and reconfigurability, the Peis-Ecology approach allows us to build robotic systems which are more flexible, adaptable, and robust than what can be achieved today. Flexibility, adaptability and robustness are clearly requirements for robots to be used in space exploration. Moreover, the Peis-Ecology approach allows a distributed robot system to be assembled "on the fly" for a given task and context, by self-configuration of the Peis which are available. An initial population of Peis can be sent, say, on a planet for exploratory purposes, including a small number of powerful ones that can deploy a large number of simpler ones. New Peis can be added later on, and participate in the formation of incrementally more powerful systems when needed. An interesting extension in this direction will be how to synchronize the hardware self-configuration of modular robots and the software self-configuration provided by the Peis-Ecology framework.

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Another future direction in the Peis-Ecology concept which may have a strong potential for space exploration is the development of a full human-robot-environment symbiotic system, as outlined in the previous section. The integration of robots, sensors, augmented everyday objects, and humans as different species into one whole Peis-Ecology would allow us to create a task-supporting ecosystem in the spaceship or on a far planet. This ecosystem would complement the life-supporting biological ecosystem, in providing physical and cognitive assistance to the astronaut in performing their everyday chores, as well as in dealing with exceptional situations. This would provide more time for the astronauts to perform their mission-related tasks. It would also provide increased safety, and offer the opportunity to engage the astronauts in entertaining and stress-releasing activities.

Here is a fully speculative attempt to put the above achievements on a time scale. By 2015, autonomous robotic technologies will start to be pervasively present in our homes, most probably in an "invisible" way, as well as most of today's computers in our homes do not manifest themselves as such. By 2020, enough knowledge will have been gained on human-robot-environment symbiotic systems on earth, to allow their exploitation in the context of space missions. By 2030, the first robot ecology would be transported and deployed on another planet — to be later expanded by sending additional robots and devices.

5 Conclusions

The idea to integrate robots and smart environments is starting to pop up at several places and under several names, including network robot systems [13], intelligent space [9], sensor-actuator networks [6], ubiquitous robotics [8], artificial ecosystems [16], and still others. 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 [13], the U-RT project at AIST [10], and the Korean Ubiquitous Robot Companion program [8]. The Peis-Ecology project presented in this paper is part of the latter effort. This project is distinct in its emphasis on the study of the fundamental scientific principles that underlie the design and operation of an ubiquitous robotic system.

The Peis-Ecology project has been active for 3.5 years at the time of this writing. A number of scientific and technological achievements have already been obtained in this context, including the three ones reported in this note: the development of an open-source middleware, the study of the integration between physical and digital interaction with the world, and new techniques for self-reconfiguration and re-configuration. Source code, videos and scientific papers relative to these achievements are available at the Peis-Ecology web site [14]. The next important step in this development will be the inclusion of humans into a Peis-Ecology. We expect that the Peis-Ecology concept may become relevant to space missions at least in two ways: as a way to deploy robotic missions for planetary exploration, and as a way to provide assistance to astronauts.

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