Scaling up Ubiquitous Robotic Systems from Home to Town (and Beyond)

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Abstract
Ubiquitous robotics is an emerging paradigm in which smart environments are augmented with robots to provide physical and information added-value services to the citizen. We discuss the challenges and opportunities in extending this paradigm from a single environment (home, factory floor) to the scale of a community of homes, a town, or even a network of towns. To this aim, we introduce the concept of *multiple robotic ecologies*. This poster is a first step in defining a scalable architecture for a hierarchy of robotic smart-home ecologies, and a framework to provide autonomous services in it.

Author Keywords
Robot ecology, Ubiquitous robotics, Multiple ecologies, Ubiquitous intelligence, intelligent environment

ACM Classification Keywords
I.2.m [Artificial Intelligence]: Miscellaneous.; D.2.11 [Software Architecture]: Domain specific architectures.

Introduction
Considerable work has been performed in the area of smart homes and ubiquitous computing to provide user centric intelligent services [1, 12]. Often, the main challenges have been how to discover the available devices, how to decide what services can be provided, and

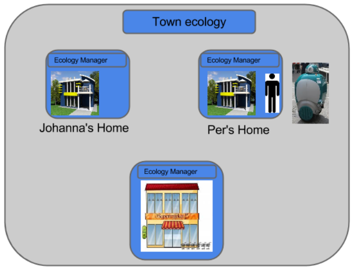

Figure 1: A town-level robot ecology as a unique, flat ecology.

how to provide them. In order to enable physical interaction, the next logical step is to enrich these smart environments by the introduction of robots.

Some work has been done in this direction, e.g., in [10, 2], where robots interact with a smart environment by using information or actuation provided by the devices in the environment. This area of research is often referred to as *networked robotics* [7] or *ubiquitous robotics* [11]. Given the predicted wider availability of service robots, robotic artefacts will soon be an integral part of smart environments. A few international projects are already exploring the inclusion of robots in the home to create value-added services, especially for elderly people [9, 8].

We call *robot ecology* a set of robots and devices which are able to discover each other's presence and capabilities, to communicate, and to form ad-hoc coalition to cooperatively perform tasks. With few exceptions [5], most experiences in realizing robot ecologies have been limited to relatively small, local domains, like a home or a factory floor. It is natural to expect that soon these systems will be required to operate in a full building, neighbourhood, town, and eventually the whole planet. A flat network organization of robots and devices cannot scale up to these levels, and some structure should be created. In this note, we put forward the idea of defining multiple, interconnected, cooperating robot ecologies. A few similar ideas have been proposed in the fields of ubiquitous computing and ambient intelligence, e.g., [6].

A Model of Multiple Ecologies

Consider the following scenario. Per is living in a home equipped with an ecology of robots and smart devices able to provide physical and cognitive services. He sends an order to the grocery store, which has its own robot ecology that helps the clerkman to fill the order. An outdoor transport robot in the district ecology brings the order to Pers door. When the order arrives, Per is at Johannas place for a visit, and he is notified by the devices in Johannas ecology — see figure 1.

A straightforward implementation of the above scenario would consider all the robots and devices in Per's home, in Johanna's home, in the supermarket and in the street as part of single ecology, so that all can discover and communicate with each other. When the system must notify Per of the delivery, it should query all the sensors within the ecology in order to find one which is able to deliver the current location of Per, then query all available devices in order to find one which is able to communicate with Per given his location — e.g., Johanna's sound system. As the size of ecology increases, this approach would clearly become unfeasible due to communication overhead, increased complexity of reasoning services, and violation of privacy.

The first step in our investigation, then, is to decompose the hypothetical overall robot ecology into a network of confined robot ecologies. In our view, each robot ecology must have a criterion that determines which device belongs to it. This can be based on location, like in the example above. But it can also be based on ownership, e.g., the ecology of Per's personal devices; or on functionality, e.g., the ecology of devices needed to track Per's position. In all cases, ecologies are dynamic: a new vacuum cleaner may be introduced in the home; Per may leave his mobile phone at home when he goes out; and the tracking ecology may recruit new devices (cameras, RFID readers) as Per moves around the town.

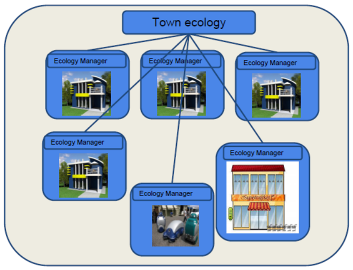

Figure 2: A town-level robot ecology as a set of multiple, hierarchical ecologies.

Approach

In order to aggregate each individual robot ecology and its functionalities, each ecology has an *ecology manager* — see figure 2. The ecology manager is in charge of recognizing its members, abstracting the information and services that the ecology can provide, and enabling cooperation and exchange of information among devices that belong to different ecologies.

Consider again the above scenario in a multiple ecology context. Per's home ecology manager will notice that Per is not at home, and it will query the Town ecology manager to get his location. The Town ecology manager will know that Per is at Johanna's by interacting with the ecology manager of Johanna's home. When the outdoor robot arrives at Per's home, Per's ecology manager requests Johanna's ecology manager to convey the message. Johanna's ecology manager finds the location of Per, based on sensors within its own ecology, and uses its own reasoning service to decide which device to use to alert Per about the grocery delivery.

Each ecology manager should provide user centric services, like communicating information to the user, alerting the user about relevant alarms or events, or monitoring user activity. The ecology manager should also advertise the services and information available in its ecology to the other ecologies. These should be properly abstracted: not all services and information should be visible, not all of the details should be exposed. Some services should be visible as an instance of a more abstract generic service, and some services may be created as an aggregate service. Some of the services may be provided by sub-ecologies, in a hierarchical way.

For instance, the service to "deliver a message to person X" can be provided and advertised as the same abstract service by two different ecologies, but this can be internally implemented in two different ways: the first ecology may implement it through a "broadcast voice message on sound system" service, while the second one may implement it through a "send robot to person and tell" service. In our view, a common ontology should be established that allow different ecologies to share information and services in a meaningful way. Ecology managers can be organized in a hierarchical, dynamic structure, thus imposing a structure on the corresponding ecologies.

Finally, privacy issues should be considered. Although this is not a concern of our initial work, we envisage to embrace an approach similar to the one used in [4] for aggregations of smart devices.

Realizing the Model

The above model is currently being implemented in the PEIS Ecology framework [10]. This framework is based on a fully decentralized shared tuple space, in which information, services and devices are uniformly represented and accessed via tuples, or general *key-value* pairs.

The extension of the PEIS Ecology framework to multiple ecologies is done stepwise. First, we consider ecologies characterized by location and in which abstraction and visibility rules are hand coded. Second, we impose a hierarchical organization on these ecologies. Third, we consider ecologies characterized by the user and by a task, in which the ecology manager is in charge of dynamically recruit and release devices. Finally, we consider the use of reasoning to determine abstraction and visibility: e.g., a new service is automatically synthesized from the ones in the ecology and a corresponding tuple is exposed by the ecology manager.

We are at an early stage, but we have already implemented a basic hierarchy of ecologies encompassing two elder care apartments. We have run experiments in our test facility to validate our current progress. The building block for the implemented system is the PEIS Middleware [3]. While we are well aware that there are literally hundreds of middleware available in the fields of ubiquitous computing, pervasive computing, ambient intelligence and robotics, we have selected the PEIS Middleware for our development because of its explicit aim to put together traditions from robotic middleware and from Ambient Intelligence middleware. The use of the PEIS middleware also simplifies the design and implementation of the ecology manager: since both information and services are uniformly encoded as tuples in the PEIS middleware, visibility and abstraction of information and services within an ecology reduce to visibility and abstraction of tuples.

Discussion

Ubiquitous robotic ecologies will soon become part of our everyday life, but scaling up this concept from home to town and beyond cannot be accomplished using a single, all-encompassing ecology. Multiple ecologies are a flexible and general way to scale. We have engaged in a study and design of a system of multiple, networked robot ecologies in the context of a large project aimed at creating real added value services for elderly citizen from the home to the town [8]. One of the distinctive features our our approach is the insistence of closing the reality gap: our system will be deployed in real environments and tested with real users in a long evaluation campaign. Scalability, flexibility, reliability, and acceptability will be the testing parameters, and eventually the winning criteria.

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