A Middleware for Ecologies of Robotic Devices

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Abstract—The fields of autonomous robotics and ambient intelligence are converging toward the vision of smart robotic environments, or ubiquitous robotics, in which tasks are performed via the cooperation of many simple networked robotic devices. The concept of Ecology of Physically Embedded Intelligent Systems, or PEIS-Ecology, combines insights from these fields to provide a new solution to building intelligent robots in the service of people. To enable this vision, we need a common communication and cooperation model that allows dynamically assembled ad-hoc networks of robotic devices, a flexible introspection and configuration model allowing automatic (re)configuration and that can be shared between robotic devices at different scales, ranging from standard mobile robots to tiny networked embedded devices.

In this paper we discuss the development of a middleware suitable for ubiquitous robotics in general and PEIS-Ecologies in specific. Our middleware is suitable for building truly ubiquitous robotics applications, in which devices of very different scales and capabilities can cooperate in a uniform way. We discuss the principles and implementation of our middleware, and also point to experimental results that show the viability of this concept.

I. Introduction

There is a marked tendency today toward the embedding of many intelligent, networked robotic devices in our homes and offices. A particularly interesting case is the recent emergence of a paradigm in which many robotic devices, pervasively embedded in everyday environments, cooperate in the performance of possibly complex tasks. Instances of this paradigm include the so called network robot systems [1], intelligent space [2], sensor-actuator networks [3], ubiquitous robotics [4], and PEIS-Ecologies [5]. Common to these systems is the fact that the term "robotic device" is taken in a wide sense, including both mobile robots, static sensors or actuators, and automated home appliances. In this paper, we generically refer to a system of this type as an "ecology of robots".

As part of a collaborative research project between the Electronics and Telecommunications Research Institute (ETRI), Korea, and the Centre for Applied Autonomous Sensor Systems, Sweden, we are developing ubiquitous robotic technologies to be used in domestic environments. In this project, 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]

When realizing these PEIS-Ecologies, there is a need to focus as much on the communication and integration of the constituent components as on the individual functionalities of each participating robot. This problem of communication and integration involves issues such as introspection and configuration of multiple agents as well as in using a middleware suitable for the application. In the literature, a large variety of middlewares [7], [8], [9], [10], [11] have been proposed for robotic applications. However, none of these existing middlewares satisfy the basic requirements necessary to realize PEIS-Ecologies and as such we require another solution for realizing this concept.

In this paper we describe the implementation of a middleware used in practice today for the realization of such ecologies of robots and discuss some of the current developments. This middleware is continuously updated and published under an OpenSource license at regular intervals.

The goal of this paper is to give a general overview of the middleware used in the PEIS-Ecology project and on our progress towards its practical realization. Accordingly, we give only a brief overview of the other research issues posed by PEIS-Ecology and refer the reader to the relevant papers [5], [12], [13] in which more details and experimental results are reported. More information can also be found at the project web site [14].

The rest of this paper is organized as follows. In the next section, we briefly recall the concept of PEIS-Ecology which is followed by a section describing the middleware requirements for this concept. In Section IV we discuss the basic concepts in the middleware and follow this with details on how the communication is implemented in Section V, an implementation of it for tiny network devices in Section VI and some of the software tools in Section VII. We take a look at an experiment run in Section VIII and, finally, in section IX we outline some future directions and new requirements posed on the middleware as more and more advanced ecologies of robots are created.

II. The PEIS-Ecology Approach

The concept of PEIS-Ecology, originally proposed by Saffiotti and Broxvall [5], combines insights from the fields of ambient intelligence and autonomous robotics, to generate a

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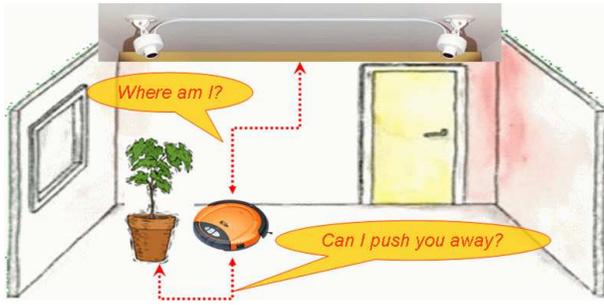[1]PEIS is pronounced /peɪs/ like in 'pace'.

Fig. 1. A simple PEIS-Ecology consisting of a vacuum cleaner, an overhead tracking system, and a plant.

Fig. 2. Two views of the PEIS-Ecology testbed.

new approach to the inclusion of robotic technology into smart environments. In this approach, advanced robotic functionalities are not achieved through the development of extremely advanced robots, but rather through the cooperation of many simple robotic components. The concept of a PEIS-Ecology builds upon the following ingredients:

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

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

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

As an illustration, consider the autonomous vacuum cleaner (PEIS) in Figure 1. By itself, the simple device can only use basic reactive cleaning strategies, because it does not have enough sensing and reasoning resources to assess its own position in the home. But suppose that the home is equipped with an overhead tracking system, itself another PEIS. Then, we can combine these two PEIS into a simple PEIS-Ecology, in which the tracking system provides a global localization functionality to the vacuum cleaner. Suppose then that the cleaner encounters a plant, and that the plant is equipped with a micro-PEIS (e.g., a mote) able to communicate its properties — e.g, size, humidity, temperature and type of support. Then, the vacuum cleaner can use these properties to decide whether it can push the plant away and clean under it.

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

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 2). 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.

Additionally, a previously existing testbed for intelligent home environments at ETRI, Korea, has also been retrofitted with PEIS-components and have been run as a PEIS-Ecology with various experiments to test reconfiguration, tiny devices and the incorporation of various automated home appliances into the PEIS-Ecology.

III. MIDDLEWARE RESPONSIBILITIES

When realizing a system containing many heterogeneous components, such as an ecology of robots, communication and cooperation become an important part. Commonly this role is played by a middleware acting as a collaboration layer between all involved devices, lifting the complexity of low-level communication and hiding the heterogeneity of the underlying systems.

Many different middlewares have been proposed for robotic applications, often from a different point of view and with different applications. Examples include the Player framework [7] providing an infrastructure, drivers and basic algorithms for mobile robotic tasks; RT-middleware [8] or Miro [9] which are both based on CORBA [10] functioning as a classic middleware but for robotic applications; or more specialized libraries such as Lime [11] focusing more towards sensor networks and less on remote actuation.

For the purpose of the PEIS-Ecology project many requirements have been posed on the infrastructure to be used. The

primary tenet for these requirements stems from the basic concepts behind the view of ecologies of robotic devices and a need for a simple interface tailored specifically to match the concepts of PEIS-Ecologies.

These requirements include: providing a shared memory model, a simple dynamic model for self-configuration and introspection, a small footprint suitable both for very small devices and larger embedded computers, and a minimalistic API easily usable by both expert roboticists as well as component programmers with little expertise in middleware and network design. Additionally, the middleware must support heterogeneous devices ranging from simple sensors and household appliances to complex robots with powerful embedded computers. These different devices must all be automatically detected and interconnected to realize an ecology and the middleware must work both for separate devices working in isolation as well as ad-hoc groups formed when devices come within communication range. Thus the infrastructure must smoothly scale as the number of devices increase and handle when individual devices as well as large groups of devices appear and/or disappear from the network.

Although not a formal requirement these constraints seem to impose also a decentralized middleware.

When evaluating previous middlewares with these constraints in mind both Miro [9] and RT-middleware [8] have problems since the Corba stack on which they are based makes it impossible to run on devices with only a few kilobytes of memory. Additionally, it is unclear if they in their current form satisfy the requirements on dynamicity and discovery when PEIS are introduced/removed from the ecology.

Likewise, the Player framework [7] is not designed for ubiquitous robotics and as such lack certain facilities required for dynamic reconfiguration. For instance, it does not provide automatic network discovery of available devices and is built using a server-client architecture. Even so, Player provides many services commonly used in the PEIS-Ecology and the devices it provide are often exported by generalized PEIS-components which acts as player clients.

As for the Lime [11] middleware, this is not usable for a full PEIS-Ecology since it lacks mechanisms for actuation. Also, the use of Java for this middleware reduces the language independence and makes it harder to interface with previously existing components using Lisp, Python and C/C++.

Since none of the classical middlewares, or eg. the robotics middlewares described above, satisfy these requirements, a new middleware called the PEIS-kernel was developed. Although developed independently this middleware has many concepts in common with Lime [11] such as using a distributed tuplespace but is tailored rather towards robotic applications and the concepts of PEIS-Ecologies instead of ambient intelligence type of applications. During the progress of the project this middleware is continuously updated and made available to the research community under an OpenSource license and is available from the PEIS project webpage [14].
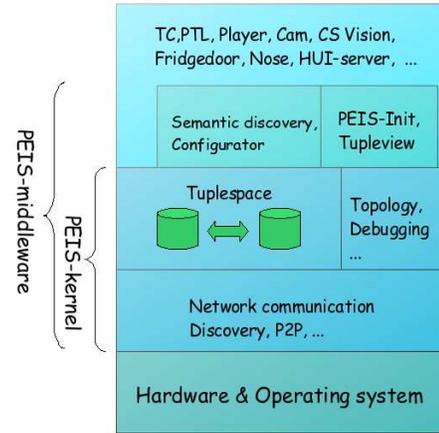

Fig. 3. The application stack used for individual PEIS-components

IV. CONCEPTS

At a first glance, the PEIS-middleware is a set of software libraries used while developing individual PEIS-components as well as a number of specific programs responsible for fixed functionalities in each PEIS and additional software to enable debugging and visualization of the current state of the ecology. The tools and libraries exist for many platforms and comprises a software stack used for implementing the PEIS-Ecology concept. See Figure 3 for a simple illustration of how these libraries and tools are related.

A. Distributed Tuplespace

From a conceptual point of view the PEIS-kernel enables each component in a PEIS to communicate and participate in the PEIS-Ecology by implementing a distributed tuplespace. This tuplespace is a decentralized version of the shared memory proposed by Linda [15], augmented with an event mechanism.

We recall that in a Linda-space a number of tuples containing keys and other data that can be stored and retrieved by any participating process using an abstract tuple where some of the fields have been initialized to wild-cards. In our version of this space a tuple has been specified to consist of a namespace, key, data as well as a number of meta attributes such as timestamps and expiration date. Separating the allowable keys into different namespaces is done not only for programming practices but is also used as an arbitration mechanism when storing and retrieving information. This is done by having the identifier for each PEIS-component as namespaces, and by using the corresponding PEIS-component as the arbiter for disambiguating all write operations to that tuple. Any PEIS-component can still store information in any namespace. We call the component corresponding to the namespace the owner of a tuple.

When components *write* to a tuple this is done, transparently by the PEIS-kernel, by sending a message to the owning PEIS-component which stores the master copy of that tuple. Depending on the order of arrival of these messages the owner
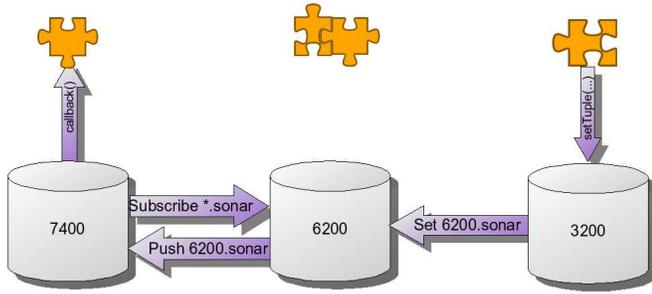
Fig. 4. Example of message passing when reading, writing and subscribing to tuples.

commits the write operations as they come in, thus avoiding synchronization issues with simultaneous writes, and sends a notification of the modified value to all other PEIS-components which are subscribed to the specific tuples. A PEIS-component must always subscribe to a tuple before it can be accessed if it belongs to another PEIS-component. These subscriptions are created by giving an *abstract tuple* which corresponds to the tuples of interest. Furthermore, since read and write operations finishes atomically there is a latency caused by network delay between when a new tuple is written and the corresponding value can be read by other PEIS-components. If a PEIS-component reads a value before the latest value has arrived over the network, it receives the old value.

Upon receiving a notification that a tuple matching an abstract tuple has been modified, the receiving PEIS-component performs two things. First, the modified value of the tuple is stored in a local database containing the last observed value of that tuple, because of network latency this is sometimes not the real latest value of the tuple. This allows local *read* operations, returning all tuples matching a prototypical abstract tuple, to complete instantly. Second, if a callback function has been registered to an abstract tuple matching the modified tuple then this callback is invoked. This invocation is performed within the flow control of the PEIS-kernel and has some restrictions on callable kernel functionalities to ensure responsiveness of the kernel. Thus the kernel implements not only a pure distributed tuple space but also allows an event based flow control.

As an example, consider a situation where we have three components with the identfiers 3200, 6200 and 7400 as given in Figure 4. Assume that the later component, 7400, have registered a subscription and a callback to all tuples that have key "sonar" in all namespaces. This is done by giving a wildcard in the first namespace field and the PEIS-kernel will send subscription messages to all relevant components. When the first component, 3200, writes to a tuple with the namespace 6200 and the key "sonar", a message is transparently sent to the PEIS-kernel inside component 6200. The receiving PEIS-kernel will then update the tuplespace with this new value and alert the PEIS-kernel inside 7400 since it's has a registered subscription. When the later receives this updated tuplevalue,

it in turn calls the registered callback function on the local processor before continuing the execution of any other PEIS-kernel related activities.

Other modifications to the Linda concept includes the use of timestamps for when tuples are created or given as user defined time stamp, as well as dates for expiring outdated tuples. To allow timestamps to be meaningful a distributed clock is implemented in the PEIS-kernel to ensure that all devices uses the same frame of reference.

B. Configurations

When creating an ecology of cooperating robotic components the issue of configuration is an important problem under much consideration. Solving this problem is akin to answering the questions of *which* components should collaborate, *what* data should be communicated and *how* these collaborations can be realized. The first two of these questions can be solved using planning techniques [16] while the last question translates into specific requirements on the used middleware to collect the information required to compute configurations as well as providing the mechanism to deploy configurations.

The first of these requirements is realized by using a fixed functionality component, PeisInit, which runs on all PEIS and provides a list of available PEIS-component which can be instantiated. This list is built up from the content of a configuration file on each PEIS listing the available resources and programs in an XML based format describing the semantics of the components. This information can easily be retrieved from the tuplespace by planners and once *which* components to be run has been determined these are started and monitored by the PeisInit. If a component is terminated abruptly this is detected by PeisInit, a failure is signaled in the tuple space and the component is restarted as needed.

For the question of *what* data to communicate and how to set up the collaborations between participating components this uses another concept of the PEIS-Ecology middleware, *meta tuples*. A meta tuple is a tuple whose data is a pointer to another tuple to be used. By implementing components to read inputs from named meta tuples in their own tuple space and produce outputs to concrete tuples we achieve an easy way of configuring components. Imagine that we have a vision component V which consumes the meta tuple V.IMAGE to produce a list of recognized objects V.OBJECTS. To allow this component to use the data produced by a camera component C we set the value of V.IMAGE to be C.IMAGE, where the later is the name of the camera images produced by C. This notion of meta tuples have been implemented in the PEIS-kernel to allow any components to be configured in a consistent way.

When a PEIS is powered on but before any communications with other PEIS have been established, it counts as an ecology consisting of only the components inside itself. As other PEIS are detected by the available communication devices and connections are established the ecologies are merged. From the component programmers point of view this is evident in the appearance of new tuples residing in the other PEIS. Similarly, when one or more PEIS are dropped from the
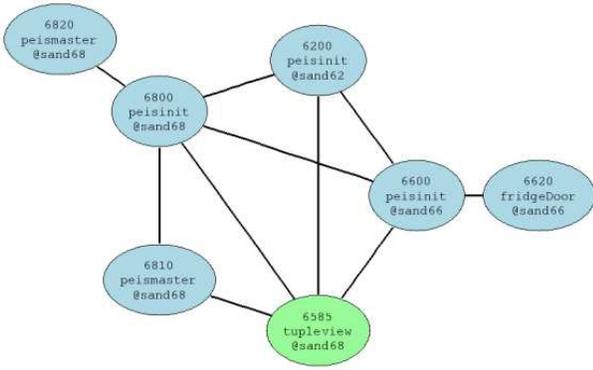
Fig. 5. Network topology for a simple PEIS-Ecology.

ecology this is noted by the remaining PEIS-component which makes tuples belonging to these components lost. They are then dropped from the local cache of tuples and attempts to modify these tuples results in an error, possibly leading to a *reconfiguration* of the ecology. Since tuples are used for closed (control) loops used in robotic devices it is important to not queue tuple modifications, otherwise unwanted actions would be performed when the PEIS are reintroduced into the ecology. This is an important distinction from how Lime treats dynamicity of components.

V. MIDDLEWARE IMPLEMENTATION

In the implementation of the PEIS-kernel a layered structure has been used to build up the various services needed. See Figure 3 for an illustration of the layers of the PEIS-kernel.

A. Communication layer

At the lowermost level an abstraction of the operating system specific communication methods isi used to provide potential communication links and device detection for shared medias, eg. using TCP/IP broadcasts on wireless lan networks. In addition to the operating system functionalities this layer also provides general services for initializations, calling functionalities periodically etc.

On top of this layer the general peer-to-peer network is implemented using standardized algorithms for eg. optimizing connectivity and performing routing.

To realize the communications necessary to implement the distributed space, the PEIS-kernel detects and connect all PEIS devices in the local environment. This is done by abstracting the available communication devices on all participating PEIS and by establishing a peer-to-peer network between all detected devices. This allows PEIS without a direct means of communication to still share tuples. See Figure 5 for an example situation when some PEIS are used to route messages between other PEIS. Note that this routing even allows devices which have mutually exclusive communication methods such as wireless lan (802.11) and ZigBee (802.15.4) to still communicate using any set of intermediate PEIS as a bridge. An example of the later case is the embedding of Tiny

sensor motes in the ecology with limited memory (10kb) and communication (802.15.4) capabilities which communicates as peers with the larger robots via a PEIS connected to both the 802.15.4 network and the wireless network. This later PEIS also serves as a bridge translating message to a more compact protocol suitable on the low-bandwidth network.

The services exported from this layer includes the transmission of routed point-to-point messages and of broadcasted messages. Message broadcasting uses a stochastic method only propagating fresh messages along a subset of the available connections, thus only consuming a global bandwidth consumption of $3N$ instead of VN where N is the number of nodes reached by a message and V is the average connectivity. Due to the use of broadcasting the total amount of bandwidth consumed per participating PEIS grows as the number of PEIS-components grows. Nonetheless, successfull tests have been performed with several hundred PEIS-components.

Since communications can go through multiple hops before reaching the destination the issue of congestion control becomes important. The method used here is based on the standard weighted random early detection (WRED) algorithm which works well to ensure a higher QoS for control messages and meta data.

B. Tuple layer

Finally, on top of the peer-to-peer network layer the actual functionalities for maintaining the distributed tuplespace and the API functionalities used by component programs are implemented. By implementing a small database for the storage of tuples each PEIS-component which uses the PEIS-kernel library can be used to store all relevant tuples. To avoid some of the problems typically associated to distributed databases the namespaces of tuples are used to circumvent many of the distribution and synchronization issues. The drawback of this approach is that if a PEIS containing information about a specific tuple is disconnected then that tuple is lost. In practice, however, this is not any major limitation since tuples are mostly used only by those components storing them.

In the implementation of these databases special attention has been given to abstract tuples. An abstract tuple is here a tuple in which one or more fields have been initialized to a wild-card value while the remaining fields have been given a concrete value. When comparing abstract tuples to concrete tuples an abstract tuple is said to match a tuple if all non wild-card fields are equal to the corresponding fields of the concrete tuple. When comparing two abstract tuples the first is said to be a generalization of the second if every non wild-card field of the second is matched by either an equal value or a wild-card field of the first, and if every wild-card field of the second is matched by a wild-card field of the first. As an example, consider the tuples $T_1 = (a, *, *)$, $T_2 = (a, b, *)$ and $T_3 = (a, *, b)$. We see here that T_1 is a generalization of T_2 and T_3 while the later two are unrelated to each other.

Abstract tuples are used for three purposes in the PEIS-Ecology middleware: Firstly, they are used whenever an application is accessing the database to query the current

value of a tuple. In this case an abstract tuple is given as a prototype and a search is made to find all tuples matching that prototype. Secondly, before a PEIS can access tuples at a remote location, a subscription to the corresponding tuples must be made. Again, this takes the form of an abstract tuple given as a prototype and the PEIS-kernel sends messages to all PEIS-components which could possibly have a matching tuple, depending on if there is a wild-card on the owner field. If a tuple is later created, modified or a PEIS-component with a tuple matching the prototype is connected then a copy of this tuple is propagated to the original PEIS-component. Thirdly, abstract tuples are used by the event mechanism to setup callbacks when tuples changes value. In practice this happens by matching all received tuple change notifications against the prototypes of all registered callbacks. Those callbacks which match the concrete tuple is invoked with it as an argument.

By using the read operation to access tuples it is possible to poll for the current value of tuples, this is commonly used within control loops where only the latest value is of interest. For event driven applications or applications responding to all tuple changes the callback mechanism is typically used instead.

VI. TINY PEIS KERNEL

By implementing the above software stack in first desktop machines and robots with powerful computers, this approach have been shown successful for scenarios including multiple robots, static sensors, and custom-made home appliances [5], [17], [18]. Some of these scenarios also included the automatic self-configuration of the ecology [16], [19]. These experiments provided us with a preliminary validation of the concept of PEIS-Ecology. In order to push the PEIS-Ecology vision further, however, we need to enable even smaller devices to be part of a PEIS-Ecology. This requires a middleware that needs to be tailored to meet the requirements of tiny networked embedded devices with as little as 4kb of memory.

For this purpose, we have extended the PEIS-middleware to allow for computationally simple devices to take part of a PEIS-Ecology as first class citizens. In doing so, we had two important requirements in mind. First, tiny embedded devices should be functionally equivalent to standard PEIS, that is, they should appear as standard PEIS to the rest of the PEIS-Ecology, using the same abstraction, communication and co-operation models. Said differently, we do not want to develop a separate, *ad-hoc* middleware model to suit the restrictions of tiny devices. Second, we want to be able to include in the PEIS-Ecology off-the-shelf tiny embedded devices, like micro controllers and WSN motes. Said differently, we do not want to restrict tiny PEIS to run on some specific, *ad-hoc* hardware platform.

This extension of the PEIS-middleware is implemented by providing a small version of the PEIS-kernel which can be run on top of TinyOS, a common operating system for motes and other tiny platforms. We refer to this slimmed down version of the PEIS-kernel as the Tiny PEIS-kernel and have performed a number of experiments with this kernel using small sensor
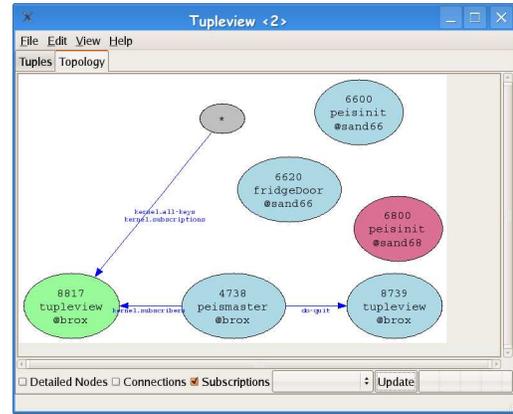

Fig. 6. Illustration of an ecology with seven components and four established subscriptions

motes and motes capable of actuation. This version of the PEIS-kernel requires at most 35 KB of programming memory, including the used TinyOS components, and about 2.5 KB of RAM. The actual footprint of the program may be smaller if an application only uses some functions in the PEIS-Kernel. For further details about the Tiny PEIS-kernel see Bordignon *et.al.*[20].

VII. SOFTWARE TOOLS

Apart from the libraries necessary to implement the PEIS-kernel a number of software tools have been developed which can also be considered part of the PEIS-Ecology middleware or which can be used for visualizing and debugging the ecology. The two most important of these tools are the PeisInit which takes care of bootstrapping and monitoring the components in the PEIS-Ecology and Tupleview which is used as a debugging tool for visualizing all available tuples, components, and connections.

The first of these two tools was described briefly in Section IV. The later tool, Tupleview, consists of a graphical user interface which can display all the available PEIS, PEIS-components and can display and allow the user to modify all tuples. Tuples with a more complex encoding, such as images, are displayed by special handlers which allows the components to use this tool as a simple user interface (display and receiving feedback) during development. In addition to displaying the content of the distributed tuplespace this tool is also used to display the network topology of all participating components and to visualize all established collaboration patterns (subscriptions). See Figure 6 for a screenshot of this tool when displaying the current configuration.

VIII. EXAMPLE RUN

As an example to illustrate the capabilities of the PEIS-Ecology concept in general and the middleware used we will look at one of the experiments performed in the ETRI testbed mentioned in Section II. In this experiment a number of PEIS were used, ranging from a simple mote sensing the light level on a plant, to automated home appliances (actuation of lights,
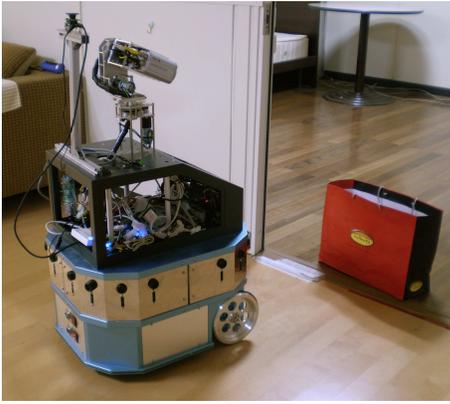
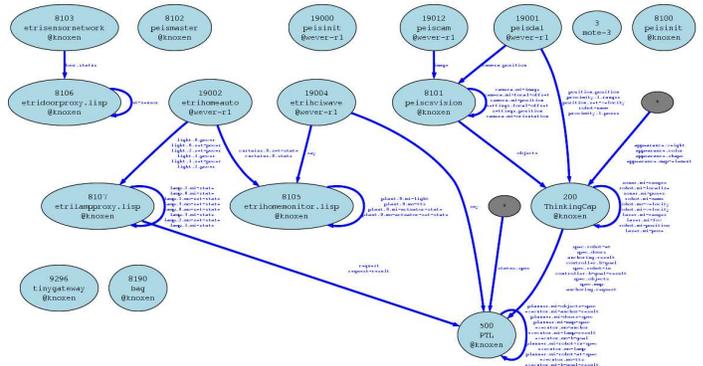Fig. 7. The robot encounters an unexpected parcel when entering the bedroom

Fig. 8. Configuration snapshot of experiment run. Here components are represented by large ovals and subscriptions given by arrows annotated with the subscribed keys.

motion sensors etc.) to a mobile robot equipped with a stereo vision head and wheel based navigation. Also number of PEIS-components (17) consisting of standard robotic and AI tools such as robot navigation algorithms, vision algorithms and high-level probabilistic and conditional planning was used in the experiment.

The execution of the experiment started with running a static configuration script consisting of a bash-script which requests all the necessary components to be started by issuing tuples belonging to the various PeisInit components that always run on all participating PEIS. Next the configuration script wrote the necessary meta tuples to setup the configuration. Note that both these two tasks could as well have been achieved using the dynamic configuration services [16] if deemed neccessary. See Figure 8 for an overview of this configuration involving 17 components and 77 subscriptions.

Next, we gave the high-level planner the goal that Johanna, the inhabitant of the apartment, should be woken up and that the robot should in the end be in the dedicated robot waiting area. This was expressed as a predicate logic goal: (AND (WOKEN-UP JOHANNA) (AT WEVER = GARAGE)). After this the planner generated the task to turn on the lights necessary for safe robot navigation (the vision algorithms require this), moving into the bedroom and issuing a wake up message using the text-to-speech services. As the final step the plan involved the robot returning back to the waiting area.

This sequence of actions was given to the execution monitor which requested each action to be performed, step by step, by the different components by issuing and listening to tuples belonging to different components. As the robot was executing this sequence of actions one component, the home monitoring component, in the ecology reacted to the changed light level reaching the mote supervising Johanna's favourite plant, and as such reacted by closing the curtains controlled by a home automation ZigBee network. During this part messages was passed between 802.15.4 devices and the wired/wireless 802.11 network via those PEIS-components which had capabilities to communicate on both networks.

Later in the execution the robot encounters an unknown package blocking the way into the bedroom, see Figure 7 and an automatic replanning to satisfy the goal was performed, receiving descriptions from all available PEIS containing their status, seen objects etc. The newly generated plan involved a query to test the weight of the box, and if possible to push it into the bedroom before resuming the original task. This plan was executed successfully thanks to a PEIS component publishing the weight and appearance of the box in the tuplespace, and thus Johanna was woken up and the robot returned to it's resting place.

IX. 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 every-day 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 [1], the U-RT project at AIST [21], and the Korean Ubiquitous Robot Companion program [4]. 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 underlie the design and operation of an ubiquitous robotic system.

In this paper, we have discussed the implementation of a middleware for the PEIS-Ecology approach. We believe that many of the requirements and techniques used for this robotic middleware are not limited to a PEIS-Ecology but also apply to any ubiquitous robotic system.

To the best of our knowledge, no comparable middleware was available until now. Today's robot middlewares are typically too heavy to run on tiny devices; and middleware for networked embedded devices are typically not powerful enough to support the complex cooperation models allowed by a PEIS-Ecology. An interesting exception is the RT-Middleware [8], for which a light-weight version has been defined [22]. However, this version runs on specialized devices. By contrast, our PEIS-Ecology middleware is intended to run on custom as

well as off-the-shelf hardware, including standard WSN motes and hobbyist micro-controller boards.

We have run a large number of experiments on the PEIS-Ecology with many different ubiquitous robotic devices accomplishing various tasks. As such, we have performed many tests and incremental development of the middleware required for the collaborations of the devices. For details about some of these experiments see [5], [18], [19], [17], [20].

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