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Multidimensional Pervasive Adaptation into Ambient Intelligent Environments

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***Abstract*—In this paper we describe the ATRACO (Adaptive and TRusted Ambient eCOlogies) approach towards next generation ambient intelligent environments. Several agents, such as a Fuzzy Task Agent with learning capabilities and an Interaction Agent collaborate in a goal-related Activity Sphere and adapt heterogeneous artifacts within the sphere in order to support the user to fulfill tasks. All components work on a dynamic Sphere Ontology, which forms the main knowledge base of the ecology. The presented prototype is able to realize the Goal "Feel comfortable at home after work" and was implemented in an existing intelligent environment.**

Keywords-ambient environnments, smart objects, ubiquitous computing

I. INTRODUCTION

For a few years, computer technology has been pervading larger parts of our everyday environment. First it spread in "technological" artifacts such as cameras, mobile phones, car radios, etc. Now, researchers consider its integration into even more commonplace objects such as clothing, doors, walls, furniture, etc. This new paradigm, called, Ambient Intelligence (AmI), offers great opportunities for an enormous number of applications such as health care, the efficient use of energy resources, public buildings, and in leisure and entertainment. AmI puts forward the criteria for the design of the next generation of ubiquitous computing environments [15]. In this paper, we claim that the next step is the design and development of totally adaptive ubiquitous computing systems, able to consistently operate in heterogeneous pervasive Ambient Intelligent Environments (AIEs). Adaptation is a relationship between a system and its environment where change is provoked to facilitate the survival of the system in the environment. Adaptive software systems use mechanisms similar to biological ontogenetic adaptation so as to regulate themselves and change their structure as they interact with the environment. This Next Generation of AIEs (NGAIEs) will inherently exhibit increasingly intelligent behaviour, provide optimized resource usage and support consistent functionality and human-centric operation (humans, as opposed to mere users, have increased requirements from a system, including, e.g., intuitive interaction, protection of privacy, fault-tolerance). Adaptive AIEs highlights various research challenges:

- Heterogeneity: In the general case, artifacts will be heterogeneous, as they will originate from different manufacturers, will probably use custom communication protocols and proprietary information representation schemes. Some of them may easily interoperate with existing networks and some may not even integrate at all. NGAIEs should provide the means to facilitate inter-operability, for example via the definition of an abstract interface or an application that can access other devices and use their functionalities.
- Transparency: Users shouldn't be overwhelmed by the AIE individual settings, the technological enhancements or the infrastructural changes according to the AmI paradigm. They should rather be supported in developing trust in technology as an enabler of their everyday activities that makes their life easier. NGAIEs should provide an adaptive degree of pro-activity combined with self-explanation and other self-* properties, so as to transparently and optimally (with respect to available resources) support people's tasks.
- Discovery & Management: NGAIEs will consist of hundreds to thousands of heterogeneous artifacts interacting via various networks. In fact, their structure will resemble that of a complex system, thus a combination of global resource discovery and local resource management will be required. Note that interaction management at a global scale will

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not be an easy target to achieve; hierarchical management schemes are promising candidates and already have been adopted by various communication protocols.

- Intelligence: Intelligence, as the primary means to achieve adaptation, will appear at various levels. For example, local resource management may require decision making mechanisms and even embedded intelligent agents. At a system scale, multi-agent systems, using semantically rich descriptions, learning mechanisms and possibly cognitive functions (such as perception, homeostasis etc) will be embedded in NGAIEs. These agents are able to recognize the users and can autonomously program themselves to meet the user's needs and preferences by learning from their behaviour to control the environment on their behalf, thus reducing the cognitive load associated with the user needing to configure and program ubiquitous computing applications.

The ATRACO (Adaptive and TRusted Ambient eCOlogies) approach presented in this paper addresses the above challenges and produces specifications and concrete realization of totally adaptable AIEs. The proposed approach deals with the above challenges by supporting five dimensions of adaptation within the AE, namely Artifact Adaptation, User Behaviour Model Adaptation, User Interaction Adaptation, Activity Sphere Adaptation and Network Adaptation. In order to achieve these levels of adaptation, we use a set of intelligent agents to support adaptive planning, task realization and enhanced human-machine interaction, based on a dynamically composed ontology of the properties, services and state of the AIE resources. In this paper, we shall show that the proposed approach provides transparency and ease of interaction with the AIE, efficient artifact discovery and management, ease for artifacts to use the various heterogeneous networks available in AIEs, and adaptation to the changes in the artifacts' characteristics as well changes to the user(s) preferences and environmental changes. The proposed approach has been validated in real AIEs.

Previous research projects have contributed to adaptation of ubiquitous applications during migration across different pervasive computing environments [14] based on changes in device and network topology [11]. They provided little or no support for adaptation based on context information. Other projects [16], [2] provided support for adaptation based on context information. In these attempts, ontology techniques, such as merging and mapping have been adopted, but they all use ontologies as static objects.

In the following section we will present the main concepts underlying our approach. Following this, the scenario and the methodologies are provided. Section IV describes the architecture followed by all main components of the prototype. Before the paper finishes with conclusions a section describing the prototype itself provides details about the implementation.

II. Concepts

We use the Ambient Ecology (AE) term for the set of heterogeneous artifacts with different capabilities and provided services that reside within an AIE [10]. Our approach is in accordance with AmI visions and aims at supporting people to achieve their goals and carry out new tasks, as well as old tasks in new and better ways. People will realize tasks using the resources offered by the services and devices of the AE.

We have defined the concept of an activity sphere, to be both the model and the realization of the set of information, knowledge, services and other resources required to achieve an individual goal within an AIE. An activity sphere has a dual hypostasis: firstly, it is a semantically rich model of an entity's specific goal and its associated tasks and a specification of the realization of this model; secondly, it is the orchestration of specific services, data and knowledge that realize this specification within the context of a specific ambient ecology. In order to achieve task-based collaboration amongst the heterogeneous members of an AE, firstly one has to deal with artifact heterogeneity, while at the same time achieving independence between a task description and its respective realization within a specific AE.

However, AEs are highly dynamic structures, the configuration of which may change, for example, because a new device may enter the ecology, or some other may cease functioning. While successful execution of tasks will depend on the quality of interactions among artifacts and among people and artifacts, it is important that task execution will still be possible, despite changes in the ambient ecology. Thus, the realization of mechanisms that achieve adaptation of system to changing context is necessary.

At the AE level, the system should support the realization of the same activity sphere in different AIEs. At the same time, the system should adapt to changes in the configuration of the ecology (i.e., a new device joining, a device going out of service, etc.). At the task level, the system realizes the tasks that lead to the achievement of user goals using the resources of the activity sphere. The artifacts should also adapt to the uncertainties associated with the changes in the artifacts characteristics, context as well as changes in the user(s) preferences regarding these artifacts and their operation. Another dimension of adaptation is the interaction between the system and the user to ease the transparency of the system to the user. A further dimension of adaptation is related to the network adaptation to allow devices and services to be used seamlessly by the ATRACO system and to simplify the discovery, management and access of networks in the home as well as in corporate environments (control, data sharing, communications, and entertainment).

The mechanism we propose to achieve the different kinds of adaptation implied by this approach is centered round the management of knowledge, which is encoded in multi-layered ontologies, which are used by intelligent agents.

III. Scenario and Methodologies

In order to come up with the ATRACO approach, we started by creating a number of user scenarios to help define the vision and user needs. Our scenario creation and analysis process followed the SUNA process [13], which is specifically targeted to teams of multidisciplinary people coming together to create new services and product concepts based on social needs, and on the possibilities offered by new and future technologies. The main aim of the SUNA process is to create one or more scenarios that best capture the envisioned service(s) and also to generate an initial set of high-level scenario-related requirements, as a precursor to more detailed user needs work and as a guide to the development of a demonstrator or prototype. For each scenario, we derived a set of related requirements, which were later combined into a common set and cross-referenced with the scenarios. Having a scenario-based set of requirements supported both the system design process, and also in creating the demonstration and evaluation scenarios. It was also used to identify specific roles in the ATRACO system, defining high-level components and designing interactions between these components. In the following paragraph we present a short version of the scenario we have created for the implementation of the ATRACO prototype.

It's 7pm now and, as usual, George comes back from work. He installed the ATRACO system one year ago and set it up for the assisting him in realizing various goals. Every time George comes back home from work the goal "Feel comfortable after work" is selected. For George this goal means that the system tries to control the heating, lighting and media systems in order to make sure the home is comfortable according to George's desires and preferences. Since the system was installed it has been monitoring his behaviour and has been learning his preferences regarding the control of heating, lighting and media systems. During the last winter the system noticed that in the winter at 7pm, it is generally "dark" and "cold" and George's preferences are to have the lights turned on with a "warm" indoor temperature when he arrives home, and he likes to watch his favourite TV news channel whilst having his dinner.Today it is a warm summer day and the adaptive system has recognized that in summer time when George comes back home at 7 pm it is usually still quite bright and very hot as the house is south facing. Hence, the system adapts by executing George's preferences (which were learnt from his behaviours) by switching on the air conditioning to cool the house while having the lights turned off. Usually George likes to watch his favourite TV news station while having dinner but this evening instead of the TV set George's favourite radio station is switched on for listening to the latest news. The ATRACO system recognized that the TV set is not working properly and tried to find something else that George might enjoy. When George is alone at home his preferred mode of controlling the TV set is by speech, so the system takes this information into account and activates speech-based interaction to control the media system instead of via the TV set interface.

A key component of the ATRACO project is to build, test and iterate versions of the system in an environment where the total user experience can be evaluated. The iSpace facility provides this space with the user firmly at the centre of the innovation process. iSpace offers a highly naturalistic setting in which users can live for extended periods of time (from a few days to a few months), and is also highly configurable for evaluating a wide range of 'lifestyle' applications. Moreover, it can be combined with different tools and methods to support the different stages of the user-centred design and evaluation process. For example it can be used to carry out basic research to refine the ATRACO scenarios, or used to formatively evaluate early prototypes of new services, through to the final validation and refinement of finished products.

One critical issue is to remove the reliance on the researcher as the main instrument for interpreting the behaviours exhibited by users living in this environment (this is true even in ethnographic studies which are still rooted in the discipline and interpretation of the evaluator). Instead, we are looking to empower the users themselves to self-analyse their experiences. For example, we have used Dervin's Sense-Making [4] approach as a means of enabling participant driven structured reflections. This has been particularly useful in highlighting usage issues arising from a range of advanced communications facilities within the iSpace. A similar approach is based on the use of cultural probes [9] where participants have used a range of different techniques (e.g., self-directed photography, labelling, diaries, pictures, etc) to capture issues arising from extended user studies. This has been particularly useful in assessing more "subtle" issues such as access to private space and conflict over control of shared resources.

After presenting the architecture of our prototype and all components that were involved to realize this scenario we describes in Section V how the prototype performs to make the user feel comfortable at home after work.

IV. Architecture

The ATRACO approach uses a Service-Oriented Architecture (SOA) that enforces a clear distinction between service interfaces and implementation. SOA has been envisioned as an evolution of the component-based architectures centred on the concept of service [6]. The SOA approach appears to be a convenient architectural style for realizing adaptable and reconfigurable systems. We adopt SOA both at the resource level (to support resources, such as devices, sensors and context to become integrated in applications) and the system level (to combine system services in the ATRACO system in order to support ubiquitous computing applications).

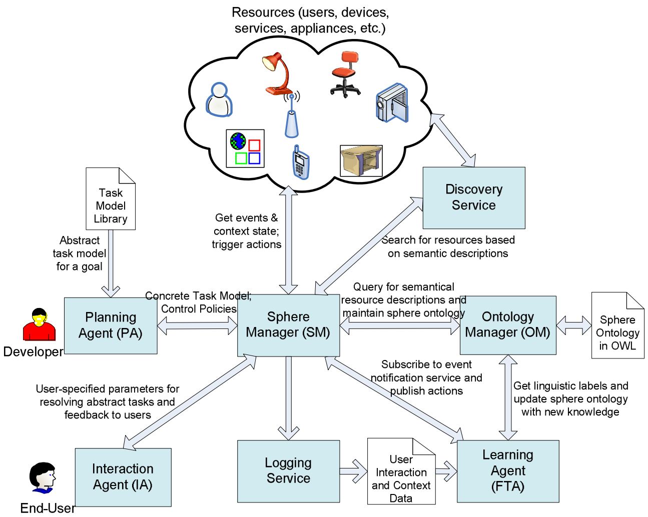

Figure 1. ATRACO Architecture.

In ATRACO we propose a combination of the SOA model with Agents and Ontologies. The agent approach complements the SOA infrastructure by providing high level adaptation to user's tasks, as an intelligent control layer above SOA. Agents have a local knowledge base that contains rules about the control of their behaviour and they may communicate and exchange messages which contain a high degree of semantics because of internal processing. In ATRACO, agents support adaptive planning, task realization and enhanced human-system interaction. Ontologies are used to tackle the semantic heterogeneity that arises in AmI spaces and provide to agents a common repository of system knowledge, policies and state. By combining the above approaches, a totally adaptive system can be developed, as we shall explain in the following sections. The ATRACO system takes users goals and contextual information into account to adapt and reconfigure in a policy-sensitive manner. The architecture that supports the realization of NGAIEs is shown in Figure 1. In the next sections we describe each one of the identified components.

A. *Sphere Manager*

The Sphere Manager (SM) forms or dissolves an Activity Sphere for a specific user goal. The SM is responsible for initializing the other system components (i.e. agents, Ontology Manager, etc.) and operates as an event service to them. An important role of the SM is to support the structural adaptation of Activity Spheres providing for the persistent achievement of the goal when changes on the type of the available resources occur. To achieve this, it monitors the state of execution of the task workflow and might change the composition of services in case of any problem (i.e. a new device joining, a device going out of service etc).

B. *Ontology manager and ontologies*

In AIEs, ontologies are used to store and convey properties, state information and knowledge of the components. We assume that several (but not all) of the ambient ecology components will contain their proprietary ontology, or set of meta-data, which describe properties, services, constraints and even state information of the component. Ontology matching is the process of finding relationships or correspondences between entities of two different ontologies. Its output is a set of correspondences between two ontologies, that is, relations holding, or supposed to hold, between entities of different ontologies, according to a particular algorithm, or individual. Current techniques for ontology matching require access to the internal structure of constituent ontologies, which must be verified for consistency, and result in static solutions (a set of mappings or a new ontology), which in addition have to be stored somewhere. But an activity sphere is a transitory, dynamically evolving entity, composed of heterogeneous, independent, usually third-party components. That is why we choose to applying the ontology alignment technique. According to [7], the ontology alignment process is described as: given two ontologies, each describing a set of discrete entities (which can be classes, properties, rules, predicates, or even formulas), find the correspondences, e.g. equivalences or subsumptions, holding between these entities.

To the best of our knowledge, this is the first attempt that utilizes ontology alignment as an integrated mechanism to achieve context-based adaptation. A similar approach is proposed in [8], where an architecture that achieves adaptation based on context information is described, but is applied to a static traditional pervasive systems architecture. The Ontology Manager (OM) of ATRACO is responsible for managing the sphere ontology (as we stated above, local resource ontologies are managed by the resource entities in a way that is transparent to the ATRACO system). Thus, under the request of the Sphere Manager, the OM produces ontology alignments, responds to queries regarding the state or properties of sphere resources, and creates inferences in order to enrich the sphere ontology.

C. *Fuzzy Task Agent*

Inhabited AIEs face huge amount of uncertainties which can be categorized into environmental uncertainties (such as the external light level, temperature, time of day, change of the sensors and actuators, conditions of observation…) and users' uncertainties (user decision for the same problem varies over time and according to the user location and activity,a group of users occupying the same space differ in their decisions in a particular situation, …). Thus it is crucial to employ adequate methods to handle the above uncertainties. In addition, there is a need to produce models of the users' particular behaviours that are transparent and that can be adapted over long time duration.

Fuzzy Logic Systems (FLSs) are credited with being adequate methodologies for designing robust systems that are able to deliver a satisfactory performance when contending with the uncertainty, noise and imprecision attributed to real world settings. In addition, a FLS provides a method to construct controller algorithms in a user-friendly way closer to human thinking and perception by using linguistic labels and linguistically interpretable rules. Thus FLSs can satisfy one of the important requirements in AmI systems by generating transparent models that can be easily interpreted and analyzed by the end users. Moreover, FLSs provide flexible representations which can be easily adapted due to the ability of fuzzy rules to approximate independent local models for mapping a set of inputs to a set of outputs. As a result, FLSs have been used in AmI spaces as in [5], [17], [12].

Within ATRACO novel theoretical developments based on the zSlices theory have been developed in order to minimise the computational costs of general type-2 FLS and to enable the application of general type-2 FLS is real world AIEs. More information about zSlices can be found in [18]. For the user behaviour adaptation, the agent will learn and adapt its rule base to face the changes in the user desires and preferences. Thus the agents will employ a modified architecture of the Incremental Adaptive Online Fuzzy Inference System (IAOFIS) technique reported in [12] while employing general type-2 fuzzy systems to handle all the faced uncertainties in AmI spaces.

D. *Interaction Agent*

The Interaction Agent (IA) (see Figure 1) offers services to communicate with the user. One of the biggest problems in AIEs is how to achieve user's acceptance. Users might indeed find the system intrusive if it controls their environment on its own. Consequently, we believe that it is necessary to inform the users of important changes, to answer their questions and to empower them with control over their environment. The IA is thus responsible for interfacing the system with the user. Of course, the IA can also be used by the system in order to get some input from the user, which leads to another interesting research issue: collaboration between the user and the system. This collaboration aspect can be used in order to support the user to select which tasks should be executed by the system and how they should be realized. In NGAIEs, the interaction context can change frequently (due to user's moves, environment changes, user's preferences, etc.). In order to provide smooth interaction, one of the most important roles the IA is to adapt the interaction to the context. In order to solve this issue, we propose to use distributed multimodal interaction widgets [3]. This way, user's task can be distributed among available modalities and devices at runtime. Furthermore, we consider speech as the richest modality within the context of NGAIEs. It is obviously the most natural way to communicate while performing everyday's life activities. Furthermore the findings of a Wizard-of-Oz experiment indicated that speech is one of the most favorite modalities within AIEs [1]. For the prototype described in Section V we have implemented a command-and-control dialogue that can be used in complement to a graphical UI to control an MP3 Player. The Interaction Agent adapts the interaction by automatically choosing the most appropriate UI.

E. *Connected Home Platform*

The Connected Home Platform (CHP) is a technological solution we have used for prototyping a typical AIE which seamlessly blends IP networking with a wealth of multi-modal home automation functionality. Within ATRACO, the CHP contributes to the realization of activity spheres under the orchestration of the SM. The CHP is able to represent the integrated AIE to the ATRACO ontology level maintaining local device and policy ontologies and collaborating with the OM to respond to queries regarding the state or properties of devices and during ontology alignments to propagate context changes to the sphere ontology.

The CHP provides a UPnP virtualization of the interfaced physical devices, which eventually belong to heterogeneous non IP networks. Considered the device types, functional profiles and event properties defined in the device representation layer as well as the availability of a standard OSGi UPnP Driver implementation it is straightforward to develop OSGi Wrapper services that export ROCob devices as UPnP devices. The UPnP Forum defined standard device profiles will be supported when available (e.g. UPnP Network Light) and new device profiles will be developed when required (e.g. Luminance Sensor).

V. PROTOTYPE

In order to test the proposed architecture, we have implemented a prototype of an ATRACO system. The iSpace at the University of Essex is used as a realworld tesbed for Ambient Intelligent Environments (AIEs). It is used to validate and evaluate the different concepts of the project. Initial trials have been done about the first version of the ATRACO architecture in year 1 and in year 2. It consists of the components detailed in the previous sections and several basic components for controlling the environments (e.g., control of lights, HVAC, music player). It was designed to make the user feel comfortable at home after work. Whenever a user enters the iSpace, the Sphere Manager creates a new activity sphere associated to the goal of making him feel at ease. To this purpose, it automatically adapts lights and temperatures to his preferences, as they are stored in his user profile. According to these preferences, the sphere manager also decides to start playing music in order to provide a relaxing atmosphere. The user preferences might change at any moment, and especially those concerning the music. That is the reason why the SM creates an IA responsible of providing User Interfaces adapted to the interaction context. In our scenario, the IA decides to instantiate a graphical user interface and a speech interface so that the user can see on his TV screen the title of the currently played music. The speech interface allows the user to change music without having to be in front of the touch screen.

Figure 2 illustrates how the user goal “Feel comfortable after work” is supported by ATRACO architecture. The SM for example assembles the necessary services using specific sensor devices in order to execute the abstract task “Sense indoor/outdoor environmental conditions”. The semantic mapping layer, represented by the OM is responsible for making semantic translations between the concepts perceived by actors and the functionality provided by the devices. The FTA executes the subtask T1bi “Deduce favorite temperature”. The role of the FTA is to support for adaptation of the given subtask according to the user desires and behavior and learn over-time in case the user overrides the automatically generated settings. The IA executes the subtask T1bii "Ask user for favorite temperature". The role of the IA is to support for a multimodal front end to the user (adaptive I/O modality).

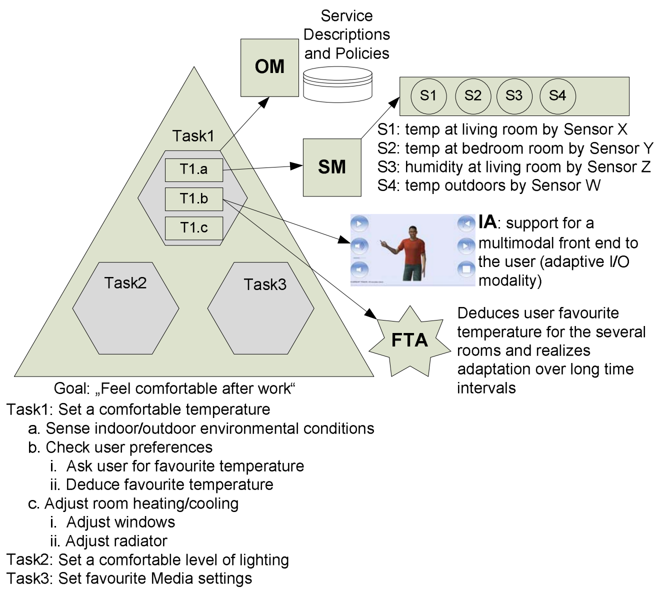

Figure 2. An example user goal supported by ATRACO.

VI. CONCLUSIONS

New generation of adaptive ambient intelligent environments require the development of new concepts and architectures. In this paper, we have presented the ATRACO approach which aims at addressing the main challenges involved with realizing the AmI vision : heterogeneity, transparency, discovery & management and most importantly adaptation. Five levels of adaptation have been identified within ATRACO. They are related to artifact adaptation, user behavior adaptation (to learn and adapt to the changing user(s) preferences and environment), interaction adaptation (to provide transparency and ease of interaction to the user), network adaptation (to provide efficient discovery and management) and sphere adaptation (which besides ontology can handle the heterogeneity in AIEs). The paper has described the architecture of the ATRACO system and a first integrated prototype. This prototype was evaluated successfully in the iSpace which has presented a proof of concept for the ATRACO system. The ongoing and future work will report on the full evaluations of the ATRACO system with multiple users in various testbeds besides the iSpace. The whole concepts of the projects and its architecture will be evaluated and validated with real user by employing a social sciences evaluation to validate and evaluate the project concepts and architecture.

ACKNOWLEDGMENT

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