4th IEEE International Conference on Digital Ecosystems and Technologies (IEEE DEST 2010)

ThinkHome: A Smart Home as Digital Ecosystem

Christian Reinisch, Mario J. Kofler, Wolfgang Kastner
Vienna University of Technology, Automation Systems Group
email: {cr, mjk, k}@auto.tuwien.ac.at

Abstract— **Smart homes have become increasingly popular in the past few years. Similarly, new buildings are nowadays planned and built following sustainability guidelines. Energy efficient residential homes have gained importance for two reasons. They contribute to the protection of our environment and they simultaneously reduce operational costs over the whole building lifecycle. However, the full potential of smart homes still lies fallow due to the high complexity of the underlying automation systems as well as the physical processes that are to be controlled. This is the motivation to review smart homes under a digital ecosystem perspective. With respect to this viewpoint, this paper proposes a system concept that applies artificial intelligence in smart homes. Main goals are to minimize energy consumption while at the same time guaranteeing user comfort. Therefore, intelligent control strategies are developed that take a multitude of parameters into consideration and operate automatically. For this purpose, an agent part populated by a society of autonomous agents that implement artificial intelligence is developed. It is supported by an ontology based knowledge representation that contains all relevant data in a structured way.**

Keywords – Smart Homes, Sustainability, AI, Ontologies

I. Introduction

For the past decade, smart homes have been an emerging issue in academic research but also in the residential building sector. The tempting vision of smart control over environments motivates home owners to integrate automation technology into their homes with the promising effects of increased comfort, peace of mind and economic benefits. Especially the latter is closely tied to reduced energy consumption. In general, the employment of respective building automation systems is an almost mandatory condition for the successful realization of sustainable (low-energy, low-emission) buildings. [1]

Still, much of the potential that would technically be available in a typical present-day smart home lies fallow. Control strategies that link sensors and actuators are not as powerful and flexible as they should be. Tuning the system precisely to the requirements of its users and taking into account the characteristics of both building structure and building automation equipment is a task reserved to experts with profound system knowledge. Moreover, optimizations are hardly ever realized in full due to the large effort required. For the same reason, necessary readjustments to new or changed requirements (e.g., when a room is remodeled from office to bedroom) are foregone almost as a rule once the system has been installed.

Apart from the technical reasons that counteract optimum system performance, also organizational factors have to be examined. Due to the complexity of the systems and the underlying physical processes that shall be controlled (e.g., temperature control), users are often unable to fully understand their system and the multitude of influence factors (parameters such as building structure, environmental conditions, system/device capabilities, etc.). Obviously, the requirements could be broken down and mapped to a manageable number of simple parameters that could be changed by the users themselves. However, in the smart home such an approach would go along with severely limiting the possible adjustments of the automation system. Therefore, the more parameters are considered, the better an optimized control strategy can be realized. This ultimately calls for a new generation of assistive systems that automatically and unobtrusively support the users to adjust their preferred building conditions. At the same time, it is nowadays mandatory to act positively with respect to the environment, thus realizing the *green building*. As a consequence, tightly integrated networked systems, improved user interaction possibilities, and foremost the introduction of semantic context and artificial intelligence (AI) have to be considered in future homes.

This work explores the topic of smart homes under the aspects of a digital ecosystem. Main driver is to support the transition towards sustainable buildings characterized by minimized energy demands and less carbon dioxide emissions. In particular, the requirements of the smart home as collaborative environment that supports the inhabitants to realize energy efficiency and comfort at the same time will be identified. The resulting system concept is termed *ThinkHome*, not last to reflect the artificial intelligence that is employed in the building. Important aspects to be considered include context awareness, conflict resolution (of contrasting system/user goals) and self-learning capabilities. Attention will also be given to design the system in a way so that it becomes understandable and usable and supports but never patronizes its users [2].

The remainder of this paper is organized as follows: In Section 2, the global system concept is presented, while the main building blocks (knowledge base and intelligent multi agent system) are discussed in detail in the subsequent Sections 3 and 4. In Section 5, the related work is treated and compared to ThinkHome. Finally, a conclusion is given in Section 6.

II. The ThinkHome Approach

The ThinkHome system is designed to fulfill all the demands of sustainable next-generation buildings identified in the previous chapter. As shown in Fig. 1, the ThinkHome system consists of two main parts, a comprehensive knowledge base (KB) and a multi-agent system (MAS). On top of the two components, the main global goals and conditions are depicted that are regarded as major influences on system design as well as for system operation. It is important to note that the separation of knowledge base and MAS reflects a logical system view. In the implementation, the system components are more tightly integrated because of their strong interdependencies. The use of well-defined interfaces helps to retain autonomy required for independent maintenance and evolution as well as a possible local distribution of components.

The knowledge base intelligently maintains all relevant data that are considered to be influence factors in a smart home. As reflected in Fig. 1, the KB is the foundation for the MAS to infer an appropriate building control strategy. It also contains the shared vocabulary used by the agents and is therefore fundamental to ground ThinkHome. Not only is it important to map the structure of the building, but there is also an imminent need to consider the desires of the inhabitants. Additionally, as one main goal is energy efficiency, it has to be possible to deduce the appropriate energy-saving action from the stored information. Hence, sufficient data has to be gathered and stored in order to satisfy the users' needs and at the same time enforce sustainability through energy efficient operation of home automation systems (HAS). The knowledge representation therefore has to keep two different types of data which are static data and dynamic data. With the help of *static data* a building model is captured and mapped to an agent-processable form. Also energy policies and user preferences are static data, as they are not likely to change frequently. For example, the user ideally enters his preferences to the system once and subsequent information is learned automatically from the daily user behavior.

Regarding buildings, especially construction physics and the surroundings and placement of the building need to be taken into account. Apart from the building structure, details of the integrated home automation systems (cf. Kastner et al. [1]) need to be modeled. The knowledge base also provides an abstraction from the underlying, probably heterogeneous, automation systems and networks, which results in easier integration of new sensors and network technologies.

The described structural information however is not enough to enable an adaptive environment as envisioned in a smart home. For this purpose, additionally a model of the current state of the building and its inhabitants is mandatory. This type of data is termed *dynamic data*. It provides information about the current state of the digital ecosystem including all its actors. This means that for given points in time, also all sensor data have to be stored in the knowledge base as well as context awareness of the system must be assured. For example, users could be tracked using RFID tags that allow to determine the inhabitant's position relative to the building structure stored as static data. Within the dynamic data branch, a considerable amount of data will be accumulated over time. This makes a suitable permanent data storage in form of a database necessary. This stored process related data can, in further consequence, be used for trend analyses or comparisons

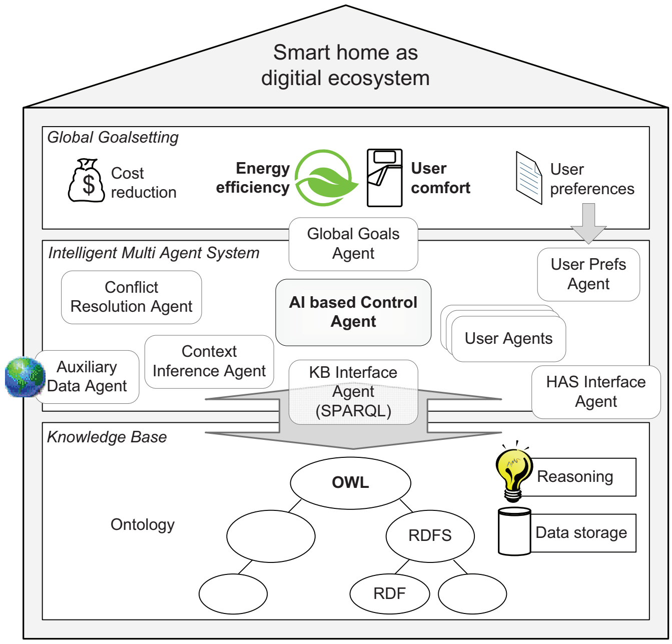

Fig. 1. Schematic Overview of the ThinkHome System Components

with historic system states (e.g., referring to the temperature behavior of a room during a last year's winter day). This promises a considerably improved performance of the smart home systems.

To realize optimized control strategies that allow maximizing energy efficiency and user comfort simultaneously and automatically, methods from AI need to be employed. An excellent means are multi-agent systems, that inherently support distributed intelligence and collaboration to act towards defined goals. Different agents are brought together by an agent based framework that also embeds the intelligent control strategies. Moreover, it caters for an interfacing with the knowledge base as well as the underlying home automation systems. The ThinkHome system is inhabited by a number of specialized agents that are responsible of solving different problem aspects. This distributed problem solving introduces a considerable degree of agent autonomy in the system, but also requires that communication and data exchange among the agents must be supported. This is accomplished using established agent based frameworks. Within this framework, the AI based intelligent control strategies are embedded. They realize the sustainable operation by constantly striving to perform an optimal mapping between the current smart home state, the given user goals and energy efficiency.

The combined ontology-based MAS approach is especially beneficial considering the encountered complexity of the involved disciplines: Home automation, knowledge representation and processing, AI and context awareness have to be coupled in an intelligent fashion. The agent based approach features cooperative problem solving in which some or all agents may take part. Moreover it provides means to encapsulate software parts that can be maintained or exchanged independently and easily. This and the required communication infrastructure are very well modeled by the agent paradigm, while all knowledge on the agents' ecosystem (i.e., the *Smart Home*) is grounded in the knowledge base implemented as ontology. Still, a comprehensive system can only be realized if a seamless integration of the intelligent MAS and the knowledge base is pursued. This calls for a thorough system specification following established guidelines and practices. Additionally, considerable effort will be devoted to the exact definition of all interfaces in the system. The following two chapters give an insight into the internal ThinkHome system concept, thereby addressing the previously mentioned topics in more detail.

III. Knowledge Base: Ontology

In information systems the division of a domain into relevant concepts and its formal representation is known as ontology (Gruber, [3]). In the field of the semantic web, data are stored in ontology documents which are formulated by different ontology languages. Standardized semantic web languages are the Resource Description Framework (RDF), the Resource Description Framework Schema (RDFS) and the Web Ontology Language (OWL). Each of these languages has its own degree of detail, while all of them find their basis in RDF. The idea of the proposed system is to apply these semantic web technologies to the home automation sector and build a comprehensive knowledge base for residential homes.

ThinkHome focuses on the energy efficiency of a building and aims to exploit the fallow energy savings potential. It is obvious that user behavior influences the energy consumption. Therefore, user contexts and emerging processes have to be modeled in the knowledge representation. Furthermore it is significant to model the environment as complete as possible in order to reach the desired system performance. For this reason, in addition to data retrieved from the underlying control networks, the structure and material of the building cannot be neglected. Already existing design artifacts such as the architect's building model (featuring building orientation, floor layout and construction details such as wall and window types) can provide most of the desired data by automatic translation into the knowledge base. Overall, it is important to create a model which is sufficiently rich in detail but at the same time does not keep too much information. This way the system remains maintainable and an adequate performance can be guaranteed.

To reflect the different data classes, the knowledge base is split into six sub-categories (cf. Fig. 2). Each of these represents a top-level concept and models a different focus of the proposed intelligent building management system.

Building: This branch of the ontology describes the energy-critical values of a building. With the help of this information, the behavior of the building in response to certain system or user-driven processes can be described. As an information source on the building characteristics, the Green Building XML Schema (gbXML) [4] is used. These data allow to take into account different building parameters, for example the

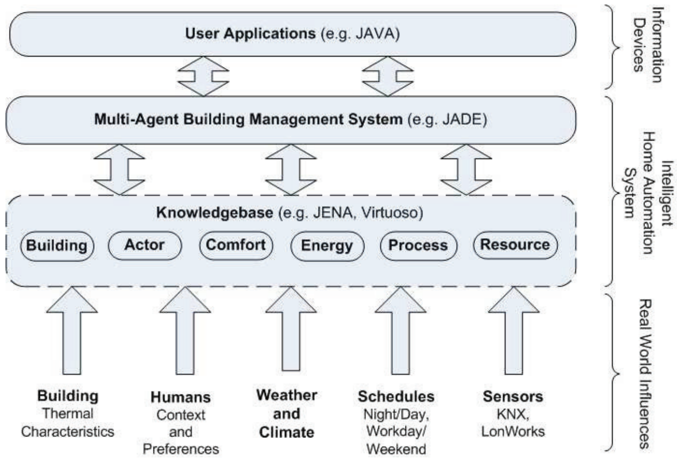

Fig. 2. Knowledge Base Top Level Concepts

thermal inertia. Additionally, ThinkHome keeps information on the building surroundings for example weather and climate data. These data are subsequently exploited to increase the energy efficiency through advanced control strategies (e.g., heating control with respect to weather forecasts).

The *Actor* knowledge part models different individuals that can appear as system users. In this respect individuals can be either in human form or also be represented by software agents that act autonomously. Human users are classified in different groups (e.g., by age, gender), while software agents can further be categorized into their specific field of application (e.g., User Preference Agent, Auxiliary Data Agent).

A part tightly coupled to human actors is the *Comfort* ontology branch. In this part comfort parameters are stored which guarantee the wellbeing of the residents. Examples of useful comfort parameters are temperature, humidity and air quality as well as air flow.

The *Energy* subdivision is used as a description of the energy impact of certain users and applications. For the users, individual profiles that correspond to their preferences and actions during a time frame are represented in the knowledge base. This part of the ontology also keeps energy schedules for different occupancy states and scenarios (e.g., day, night, weekends, holidays).

For the tasks that are to be executed either by humans or by the system, an own ontology subtree is considered. This *Process* concept holds atomic activities which can be combined to form action sequences of varying time frames. For human individuals this can include the occupancy of rooms or activities performed in the building. For the system it comprises different processes which the building can automatically invoke in order to enforce energy-saving policies.

The final ontology part to make the knowledge base complete is the *Resource* sub-ontology. This fragment holds information about all different underlying home automation systems as well as interaction systems. It also holds the characteristics of control networks that are found in the building as well as the actual state of the sensors.

Auxiliary universal concepts which cannot be associated with one of the main branches are defined on the top-level as own ontology-subtrees. An example is the concept of time that is represented by the Time Ontology proposed by the W3C [5].

The combination of these sub-categories forms the global ThinkHome knowledge base. The knowledge representation is modeled in OWL and can subsequently be used to query the stored data with the help of intelligent software components (cf. Fig. 1). Basic reasoning is carried out by a knowledge base reasoner in order to provide a minimally redundant and integrated ontology. The reasoner can further be used to infer implicit knowledge from the description of a newly integrated element. For example, after adding a new human actor to the system, the reasoning mechanism can deduce appropriate default comfort parameters according to age and gender. This ensures an adequate system behavior from the start even if new or unknown components are introduced.

For implementation of the knowledge base the use of a framework such as the JENA Semantic Web Framework [6] is forseen. It provides a set of operations on the ontology documents as well as mechanisms to transfer historic data to a permanent storage. In the proposed system, a dedicated permanent storage server system is considered for keeping the vast amount of historic sensor data. One possible candidate to take over the storage task is the Virtuoso Universal Server Project [7]. Other higher level tasks such as the intelligent combination of user actions and the enforcement of appropriate energy saving or comfort strategies are supported by the KB but executed by the intelligent agent system building on top. The intelligent MAS uses the ontology as a shared virtual world in which each agent can ground its beliefs and take actions [8].

IV. Intelligent Multi-Agent System

An agent based framework is home for a set of agents that cooperate to achieve ThinkHome's primary goals energy efficiency and user comfort. It therefore bears the artificial intelligence part in it that decides on the control strategies. Through dedicated agents it uses as well as provides access to the knowledge base and also acts on behalf of the users. The agent system part also interfaces with the underlying home automation systems, integrates auxiliary data sources, and implements context inference and conflict resolution services.

For a technical perspective, all functions are realized by dedicated agents. They are hosted by a software based agent framework that provides them with well-defined communication services (e.g., JADE [9]). The internal specification of the agents follows proven concepts that feature standardized elements and software tools (e.g., JADEX [10] or JACK [11]). Using them, the internal goals, plans and reasoning within the agents can be precisely modeled. The specification process of the intelligent MAS follows the well-known Prometheus methodology [12]. Prometheus provides formal guidelines and a formal notation for a detailed agent and system architecture specification. Yet, the specification is kept independent from any specific implementation technology.

The following list gives an overview of all agents that are mandatory for successful system operation. The different agent tasks are described in natural language. Note, that a single list item (or ellipse in Fig. 1) may stand for a set of agents that together solve the problem indicated by the name.

AI based Control Agent: The AI based Control Agent is the core point for the sustainable, energy efficient operation of the smart home. It is responsible for execution of the intelligent control strategies that control the building state. For this purpose, the agent takes into consideration the global goals, user preferences, current system state and auxiliary data (e.g., current solar radiation) to compute appropriate actions for the underlying home automation system. The control decisions will be made upon both simple control algorithms as well as using artificially enhanced ones, e.g., artificial neural networks or fuzzy logic. To master this crucial task, the Control Agent acquires information from several other agents in the system, striving to get a global view of the whole system state. For example, the agent retrieves sensor values from the home automation system and enhances them with semantic information that is contained in the KB.

User Agent: The User Agent acts on behalf of users and strives to enforce comfortable environmental conditions for its owner. To control the indoor conditions of a building in an energy efficient way it is most important to reduce the control efforts to the lowest amount possible so that the users still feel comfortable. Therefore it is mandatory to be aware of the presence, preferences (cf. User Preferences Agent) and habits of all residents. Embedded in the User Agent is a learning component that is responsible for learning the preferred environmental conditions, habits as well as typical situations and scenarios of its owner during operation. In this task it is supported by the Context Inference Agent. Additionally, the User Agent accepts user feedback and is capable of integrating this feedback. Persons that are not registered in the ThinkHome system are assigned an anonymous, temporary User Agent that assumes default values and is dispatched to cater for his/her needs during the visit.

User Preferences Agent: This agent provides an interface to the user to enter, review or change his/her preferences. In the agent society, it is tightly coupled with the User Agent.

Global Goals Agent: Similar to the User Agent, this agent advocates the global goals when control decision shall be made in the MAS. It is therefore a key component for the realization of energy efficient building operation.

Context Inference Agent: The agent can set actions in context with users, location and time, i.e., it can identify activities and build a model of the current situation. This context inference is required for an adaptive, intelligent building control. For example, persons can be identified when entering the building, tracked within the building and their location is continuously reported to other agents. These can then act upon this information, for example, turn off the lights when all persons left a room.

Conflict Resolution Agent: The Conflict Resolution Agent resolves potential conflicts. These conflicts are likely to occur among contrasting global goals, especially energy efficiency and user comfort, as well as between user preferences of different users that are present at the same time. In any case, the agent needs to employ strategies that find acceptable trade-offs and also be considerate of receiving all user feedback. Obviously, this agent is crucial for system acceptance and will therefore be well defined.

Auxiliary Data Agent: This agent provides an interface to import additional data from miscellaneous sources, for example Internet based web services. A typical example is the integration of weather forecasts in the control strategies obtained from a local weather station or over the Internet.

KB Interface Agent: The agent interfaces to the knowledge base and handles all data exchange across the system parts. If initiated by other agents, it uses SPARQL [13] queries to obtain information from the knowledge base. It can parse the query results and communicate them to other agents involved.

HAS Interface Agent: The HAS Interface Agent acts as interface between the agent society and the underlying automation system of the smart home. On the one hand, this concerns the execution of the control strategies computed by the AI based Control Agent. It therefore controls the HAS to adjust the respective environmental conditions in the building. On the other hand, it functions as a feedback interface from the building to be controlled back to the ThinkHome system. This includes the sensing of process values (e.g., change of room temperature) and generally collecting all information provided by the automation devices.

V. Related Work and Summary

As research in the area of intelligent home automation is growing, there already exist some preliminary works on the use of multi-agent systems or ontologies in automation systems. In the MavHome project, Cook et al. [14] propose using a MAS in the home that is capable of learning inhabitant behavior. Methods such as data mining and event sequencing (episodes) are employed. Data is gathered using agents that communicate with the help of the Common Object Request Broker Architecture (CORBA). Actions are triggered based on hierarchic Markov models. Similar tasks are distributed to agents in the MASBO project [15]. Also Davidsson and Boman [16] proposed a MAS in which different agents pursue the goal of energy efficiency. They specified Personal Comfort Agents representing the inhabitants, Badge System Agents for user tracking, and, Environmental Parameter Agents to control the indoor conditions. A rudimentary evaluation is given based on a simplified room model. In [17], Liang et al. describe a basic agent based framework for smart homes. Five agents are differentiated: Space Agents interface with devices, Function Agents shall guarantee the realization of global goals, Personal Preference Agents make use of user preferences when executing control strategies, Resource Access Right Control Agents provide a lookup service, and, an Environment Variable Server Agent supports data acquisition over the internet. Zhang et al. [18] rely on the OSGi (formerly Open Services Gateway initiative) platform to implement an agent based framework. The approach targets the integration of different heterogeneous domotic devices and supports remote device control and fault diagnosis. UPnP (Universal Plug and Play) in combination with an agent framework are used for device discovery, registry, and management. Possibilities for the use of artificial intelligence in the home are described by Augusto and Nugent [19]. Similar to MavHome, the detection of discrete events is of importance. Event sequences are then derived using machine learning mechanisms such as decision trees and case based reasoning. All projects listed above have in common that they describe similar approaches on how to use agents for different tasks in buildings. Still, none of them proposes a comprehensive strategy how knowledge is managed in the system. Also, most approaches lack details on control strategy parameters and or focus on particular sub-challenges only, e.g., MavHome specializes on context awareness.

However, also preliminary work that proposes agent systems in combination with ontologies can be found. In [20] Chen et al. propose an ontology-based system for a smart meeting room. They introduce several use-cases for a meeting room and employ context reasoning. Another approach for ontology-based context reasoning is taken in [21]. The suggested system uses the OWL for context modeling. Benta et al. [22] describe a multi-agent system working with an ontology mapping of the environment. The work focuses on context awareness as well as user tracking and especially user behavior. Retkowitz in his work [23] describes a possibility to integrate heterogeneous services in smart homes with the help of an ontology. It is based on an ontology mapping for semantically equivalent service interfaces. In [24] the respective system architecture is specified in more detail. Different service layers are exemplified with the help of use cases. Main achievement are the unified service interfaces that enable a continuous specification, configuration and deployment process. The authors of [25] propose a system which is based on J2EE and also uses multiple agents in combination with an ontology. The focus of their system is put on the industrial sector, in particular targeting logistics and scheduling applications. Nevertheless, their study is a rare example of the practical application of an ontology-based multi-agent approach in a large real-world system. The article [26] proposes an ontology that allows a vendor-independent representation of a domotic system (DogOnt). In addition, the authors propose a reasoning mechanism that supports the integration of new components into existing systems. The integration in a multi-agent system as well as energy efficiency deliberations are not considered.

Finally, some work that at least touches the architectural constraints for ontology-based smart home control can be found. The DogOnt project mentions an extension to the architectural domain but does not implement it. The DomoML project [27] proposes a taxonomy which emphasizes household appliances and takes into account their location, but it does not deal with the building structure explicitly.

Although all articles specialize on one topic or another, none of them touches all important aspects of intelligent smart homes. Different MAS are specified, but mostly fail to ground agents in a knowledge base. Ontology based approaches mainly support context awareness and integration of heterogeneous sensor networks. Even if extended with agent systems, important considerations on building structure, user behavior or energy-related topics are still not modeled in the knowledge base. Nevertheless, selected project parts are considered as a starting point for the specification of the respective concepts in ThinkHome. This concerns especially context awareness and artificial intelligence mechanisms.

Main advantage and distinguishing characteristic of the ThinkHome system is therefore the comprehensive approach that takes into account all important aspects collectively: a knowledge representation modeling energy, user, context, building, comfort and automation system aspects complemented by an intelligent MAS that autonomously makes use of these data to control the smart home in an energy efficient and comfort oriented way.

VI. Conclusion And Outlook

The ThinkHome project is geared to exploit automation systems and AI mechanisms to improve the sustainability of buildings. It is designed in a way to relieve the smart home inhabitants from cumbersome tasks such as readjustments of their preferences by introducing learning capabilities and context awareness in the home. Self-configuration of the smart home is achieved by integrating domain knowledge of architecture and building physics into the ThinkHome knowledge base. The system works towards energy efficiency and user comfort automatically, yet always acknowledging the residents' desires. This is achieved by a self-managing and adapting society of autonomous acting agents. The smart home is turned into a digital ecosystem that is grounded by an ontology and that actively includes its users into the decision process. This and the inclusion of architecture and building characteristics in a multi-agent based system make ThinkHome an unique approach.

As an immediate next step, intensive work will be devoted to the definition of sustainable use cases that are only made possible through ThinkHome. This effort will be followed by a more fine grained specification of the agent system and the knowledge base. Design methodologies such as Prometheus will be followed. As ThinkHome is a comprehensive approach involving many research disciplines, also the integration of proven approaches, e.g., algorithms for context awareness, will be investigated. Furthermore, concepts how to make system decisions transparent to users shall be developed. This includes the modeling of the interaction between system and users.

Acknowledgements

The work presented in this paper was funded by the HdZ+ fund of the Austrian Research Promotion Agency FFG under the project 822170.

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