The models and their vocabulary for the Adaptive Augmented Reality A^2R
Los Modelos y su vocabulario para la Realidad Aumentada Adaptativa A^2R

Maritzol Tenemaza
National Polytechnic School
Departament of Information and Computer Science
Quito, Ecuador
Email: maritzol.tenemaza@epn.edu.ec

Angélica de Antonio
Polythecnic University of Madrid
Intelligent Virtual Environment Laboratory
Madrid, España
Email:angelica@fi.upm.es

Jaime Ramírez
Polythecnic University of Madrid
Intelligent Virtual Environment Laboratory
Madrid, España
Email:jramirez@fi.upm.es

Abstract—**Adaptive Augmented Reality is an emerging technology that can support users in their daily life with useful information in real time activities. However, one of the problems identified is the lack of a formal definition of the models required for the development of a A^2R system. Therefore our aim is to propose a detailed definition of the models needed for this type of systems. To achieve this goal we started with a review of user adaptive systems throughout history, finding that adaptive Web systems have their own proposals for models and features, as well as for adaptation mechanisms of both presentation and navigation. Nevertheless these results do not fully satisfy the needs of A^2R systems, as the scope for adaptability in A^2R systems is wider than in typical web systems. We present an initial proposal of the required models for A^2R. Moreover, in the search for a formal ground in the definition these models, we explored state of the art ontologies, particularly ontologies related to user and environment modelling, two key aspects in A^2R, and we analysed to what extent our models are covered.**

Resumen—**Realidad Aumentada Adaptativa es una tecnología emergente que apoya a los usuarios en las actividades de su vida diaria con información útil y en tiempo real. Sin embargo, uno de los problemas identificados es la falta de una definición formal de los modelos requeridos para el desarrollo de los sistemas A^2R. Por lo tanto nuestro objetivo es proponer una definición detallada de los modelos necesarios para este tipo de sistemas. Para lograr este objetivo iniciamos con una revisión de los sistemas adaptativos al usuario a través de la historia, encontrando que los sistemas web adaptativos tienen sus propias propuestas para modelos y características, así como mecanismos de adaptación para la presentación y navegación. Sin embargo estos resultados no satisfacen las necesidades de los sistemas A^2R, ya que el alcance de los sistemas A^2R es más amplio que el de los sistemas web típicos. Presentamos una propuesta inicial de los modelos requeridos para A^2R. Además, en la búsqueda de una formal definición de estos modelos, exploramos el estado del arte de las ontologías, particularmente las ontologías relacionadas con el usuario y el entorno de modelamiento, dos aspectos claves en la A^2R, y analizamos cómo extender nuestros modelos.**

I. Introduction

Augmented Reality allows user to see the reality with overlaid digitally synthesized objects. Adaptive Augmented Reality (A^2R) are augmented reality systems that respond to the user's interests and context with useful and effective real-time information.

The A^2R needs to deal with a fully mobile and dynamic environment, and at the same time these systems have to be able to adjust themselves to each user in the universe of people, for example, by selecting the most suitable multimodal presentation of the relevant information for each user.

Currently the presence of smartphones, AR glasses, sensors, cloud computing complemented with the amount of information provided by people while working online provide the basis of the A^2R.

A^2R is an emerging technology that can support users in their daily with useful information in real time activities. However, one of the problems identified is the lack of a formal definition of the models required by a A^2R system. Therefore our aim was to make a proposal for a definition of models needed for this type of systems.

To achieve this goal it was necessary to review user adaptive systems throughout history. We first analized adaptive hypermedia systems and then adaptive web systems. After that, we concluded that Web systems bases their success on the track of the digital fingerprint left by users as long as they browse the web and social networks. Web systems have their own proposals of models and features, as well as adaptation of both presentation and navigation. Nevertheless these results do not fully satisfy the needs of A^2R systems.

The scope for adaptability in A^2R systems is wider than in typical web systems. Taking into account that we presented our proposal of models for A^2R and we explaind to what extent these models are covered by state of the art ontologies related to user modeling. After that we expose possible lines of research derived from our conclusions.

mds
September 17, 2014

II. Basic Concepts of Augmented Adaptive Reality

According to Azuma [1], the term augmented reality appeared as an alternative to virtual environments or virtual reality systems. Virtual reality immerses users in a synthetic reality in a a way in which they can no longer see the real world that surrounds them. In contrast, augmented reality allows users to see the real world while they are interacting with superimposed virtual objects. Azuma specifies three fundamental characteristics of AR: a) it combines the real and virtual; b) users interact in real-time; and c) it offers 3D representations.

Adaptive augmented reality is an adaptation of augmented reality applied to a real-time context and the personal characteristics of the user [2]. While the quantity of data needed is not predictable and strongly depends on individual tasks, the minimal application should offer adaptive features [3]. Some researchers are already studying how to adapt augmented data to the users context and preferences [4].

III. Analizing the Current State of Adaptability

The Google Glass software prototype appears to be a full-blown A^2R application. However, the literature on A^2R have not reported yet an analysis of necessary models and their representative features. On the other hand, adaptability has been successfully implemented in web applications. For this reason, we are impelled to begin our research both with hypermedia and web applications.

Once the adaptability models have been initialized, they need to be updated during program execution. For this reason, we will also address the types of adaptation in web applications.

A. Adaptability Models

In adaptive hypermedia applications, Martins [5] and Benyon [6] have proposed the following models for applications adapted to users:

- **The user model** describes personal data, knowledge bases, preferences, abilities, emotional states, and many other features of the user and her or his context.
- **The domain model** represents the domain of knowledge which applications use.
- **The interaction model** represents the interaction between the user and the application. Data stored in the interaction model are used to infer user characteristics in order to update and validate the user model (UM).

This division into models promotes a better understanding of the adaptation process.

Below we will identify the different characteristics of users and their contexts that are useful and relevant for adapting applications to their interests and needs.

B. User Characteristics Relevant to Adaptation

1) Features of the User relevant to Adaptation: The most popular and useful features for user models are the following ones: *User knowledge, interests, objectives, background, and individual traits* [7]. Below we will review them one by one.

1) **User Knowledge**
   User knowledge is very important and depends upon the applications domain [5] [8]. Yet it is variable in nature. The user can both acquire new knowledge and forget things. This can happen in the interim between sessions. An adaptive application based on user knowledge has to recognize changes in the state of the users knowledge, and thus update the user model.
   There are several types of *models* that represent user knowledge:
   - ***Scalar model***. This represents the users degree of familiarity with the domain as a value in a quantitative (numeric) or qualitative (good/average/poor/none) scale. The value is usually derived by self-evaluation or by an objective test.
     The disadvantage of the scalar model is its lack of precision. A domain may have different subdomains, and a user may be an expert in certain aspects of the domain but not in others.
   - ***Structural model***. The most recognizable form of the structural model is the *overlay model*. This model represents user knowledge as a subset of the domain model and reflects an expert knowledge of the domain.
     Each fragment of the domain model stores a knowledge *estimate* in one of the following forms:
     a) *Old form,* using dichotomous representations: yes/no, knows/does not know, etc.
     b) *Modern form,* that stores the degree in which the user knows the domain fragment:
        - *Qualitative* (good / average / poor).
        - *Quantitative* (as a probability).

     According to *the nature of the users knowledge,* structural models can be grouped in two:
     a) *Conceptual domain:* facts and relationships represented as a network of concepts.
     b) *Procedural domain:*
        - *Knowledge for problem-solving,* represented as set of restrictions.
        - *Knowledge for evaluating the exactitud of a solution,* represented as set of restrictions.

     In its general form, the overlay model is used to:
     a) Measure to what extent a user is familiar with a certain concept.
     b) Determine what the probability is that a user can apply a certain rule.

     The disadvantage of the overlay model is that rarely does the users knowledge coincide exactly with a subset of the knowledge domain.

- ***Error model***. The model that has received most attention is an error model known as the *perturbation model*. This model assumes that many incorrect perturbations exist for each component of the knowledge domain. For this model, it is not enough to declare the components of the knowledge domain. One must also identify specific knowledge errors. For this reason, error models represent both correct and incorrect knowledge. In conclusion, error models allow applications to recognize erroneous solutions to problems, then offer useful and customized explanations.
- ***Genetic algorithm***. This reflect developments in user knowledge, from the specific to the general. Its practical use has been limited.

2) **Interests**
Interests are useful criteria for data recovery and for filtered adaptive applications that manage large volumes of data [9] [8].
The approaches for representing user interests are:
   a) *Approximation at the keyword level,* a technique used for almost all adaptive applications that recover and filter data. Interests are represented as a keyword vector, a useful approach for open collections.
   b) *Approximation at the concept level,* this is similar to the approach used by the overlay knowledge model. It permits designers to model different aspects of user interests and, thus, arrive at a more exact representation of interests.
   This model separates interests into distinct themes. For example, in applications that personalize news items, we can model users interests by sports, current events, etc. Semantic links are very important to this type of model. These approximations are useful for closed collections.

3) **Objectives and Tasks**
In the near term, users are interested in fulfilling objectives and completing tasks. Depending on the application, users may have an immediate need to access data (data access systems), or are participating in a training program (educational systems). User objectives are highly subject to change. Objectives may change between consecutive periods of accessing the application, or while using the application during the same session. There are two approaches to modeling objectives in adaptive applications:
   a) *A catalog of goals,* this is similar to the overlay knowledge model. At the core of this approach is a predefined catalog of possible user objectives or tasks recognizable by the application. Often, this catalog is nothing more than a set of independent objectives.
   b) *A hierarchy of goals,* high-level objectives are progressively decomposed into lower level objectives defined mostly by short-term goals. There must be an objective at each level of the hierarchy. The application must recognize and mark the objective as a current one in order to apply adaptive rules.

4) **Background**
The users background contains a set of characteristics related to her or his prior experiences, often including professional information, responsibilities, and her or his work experience in related areas.
Background information is often used to adapt content in adaptive searches and to support navigation.
By its nature, the users background doesnt change while they are accessing the application. But it is not possible to deduce it simply by observing. Rather, the user must explicitly deliver the data.

5) **Individual Characteristics**
These are the characteristcs that, taken together, define a person as an individual. For example, they include aspects of the personality (introverted/extroverted), cognitive styles (holistic/serial thinker), cognitive factors (capacity to memorize), and learning styles [9]
Similar to the users background, individual characteristics are generally stable. Either they never change or they may change over a long period of time. However, unlike background, individual traits cannot be extracted simply by interviewing the user. One must design rigorous psychological tests. Many researchers agree that it is important to model individual characteristics and use them in adaptive applications [9].
The modeling focuses mainly on two groups of characteristics:
   a) *Cognitive styles*
   According to Brusilovsky y Millan [7] and cognitive style is the preferred research focus for organizing and representing information used to personalize the Internet experience and other customizations.
   The different cognitive style are: dependent/independent, impulsive/reflexive, conceptual/inferential, thematic/relational, and analytic/global. For adaptive hypermedia, the most common styles being investigated are field dependence/independence and holistic/serial thinking.
   By its nature, cognitive style influences the human capacity to access information according to how it is organized and nagivated.
   b) *Learning styles*
   Brusilovsky-Millan [7] and Brusilovsky [9], define learning styles as the form by which people prefer to learn. It is still not clear which aspects of learning style need to be modeled, nor how applications can be differentiated according to different learning styles. Most of the work being done in adaptation based on learning styles is exploring

adaptive content options. Researchers are trying to match users that have a specific style of learning to appropriate content according to style [10].

6) **Emotional state**
Brusilovsky-Millan [7] finds the concept of emotional state useful for capturing data about user motivation, frustration, or commitment. Applications can capture data from user interactions or sensors. In contrast to individual characteristics, emotional state is temporary and variable.

C. Adaptation Types

Adaptation of content, presentation, and navigation concentrates on the user model. As we have seen, the user model represents the users preferences, interests, user knowledge, objectives, etc. At the same time, these can change between logins or even during the same login session. Changes manifest themselves as the user interacts with the system through navigation choices, Internet searches, and interaction with social networks. Changes can also be recognized in a specific context by identifying restrictions and representations.

The different types of adaptation are:

- **Content Adaptation.** In adaptation of content, the data delivered are modified with the goal of fulfilling an access requirement [11] [12]. Customization of content means presenting different data for different users. The data presented should be only that which is essential to the user, depending upon their preferences.
- **Adapting the presentation.** Once the most relevant content is selected and has been structured according to the context under which the user is interacting, the content is organized so that it can be used for adaptive data presentation [11] [12].
- **Adapting Navigation.** Once we identify the users needs, objectives, interests, and user knowledge and capture them in the user model [13], we can tackle the adaptation of navigation. A websites linkage structure can be modified to facilitate data searches. The idea is to dynamically generate shorter search paths that provide the required data [12]. In other words, we should select the links most relevant to the user, changing the original navigation framework in order to reduce web page relationships.

IV. PROPOSED MODELS FOR A^2R

In this section we will present our proposal of models for A^2R. This proposal extends previous works in web applications with information that becomes relevant when considering A^2R systems. Thus, we propose the set of models presented in Figure 1.

Here is a description of each model proposed:

- **User model**. In terms of the personal and cognitive data represented, the user model is similar to that of web systems. However, the user model in A^2R goes far beyond, because the user's physical and physiological features and behaviour must also be taken into account and analysed in real-time. Data such as the stride length of the user, his/her state of health, and other important characteristics are used for A^2R analysis. The model must receive input data both prior to interaction and during user's engagement with the system. Therefore, it is necessary to define rules for updating the model accordingly.
- **Context model**. This model represents a snapshot taken from the situation in which a user is using the system in a particular environment in a particular way. It is different from a traditional context model because it takes into account the real environment.
- **Interaction model**. This model represents the evolution of the user-system interaction. What distinguishes it from context is that context is an instant snapshot, while the interaction model registers the history of user-system interactions and the evolution in the context. It contains a history of important events and serves as a data source for enriching the others models.
- **Environment model**. This model represents attributes of objects, persons, locations, and all other aspects related to the real environment in which the user uses the system.
- **Adaptation model**. According to [12], the system should adapt content, navigation and presentation. Based on this requirement, the proposed model defines how to adapt output data coming from the content model taking into account interests and other user's characteristics represented in the user model. Moreover, it will consider defined restrictions in the environmental model and, if necessary, data from the interaction model. The resulting data should be presented in a user-friendly, multimodal form, without forgetting the importance of the human-computer interface, both for mobile phones and others A^2R devices.

V. ONTOLOGIES APPLIED TO MODELS FOR A^2R

An ontology is a computational model that describes a conceptualization of the world [14].

Ontologies become important in A^2R because they can provide a formal vocabulary for specifying A^2R models.

To the best of our knowledge there is only one work [15] that proposes ontologies to formalize A^2R models and rules to update them. It defines several A^2R applications that utilize ontologies:

- A search for a defined resource in a defined area within the users environment. For example, in an office in which there are several printers, the user would define an area and the system would identify which locations have available printers in that area. The system would use a distance criterium between the user and instantiated printers to determine which printers to display.
- A second application would retrieve relevant documents from a library or archive. The context model helps to determine which documents should be displayed, based on the users interests.
- A third application would display human-assisted virtual environments for senior citizens who live alone, in cases

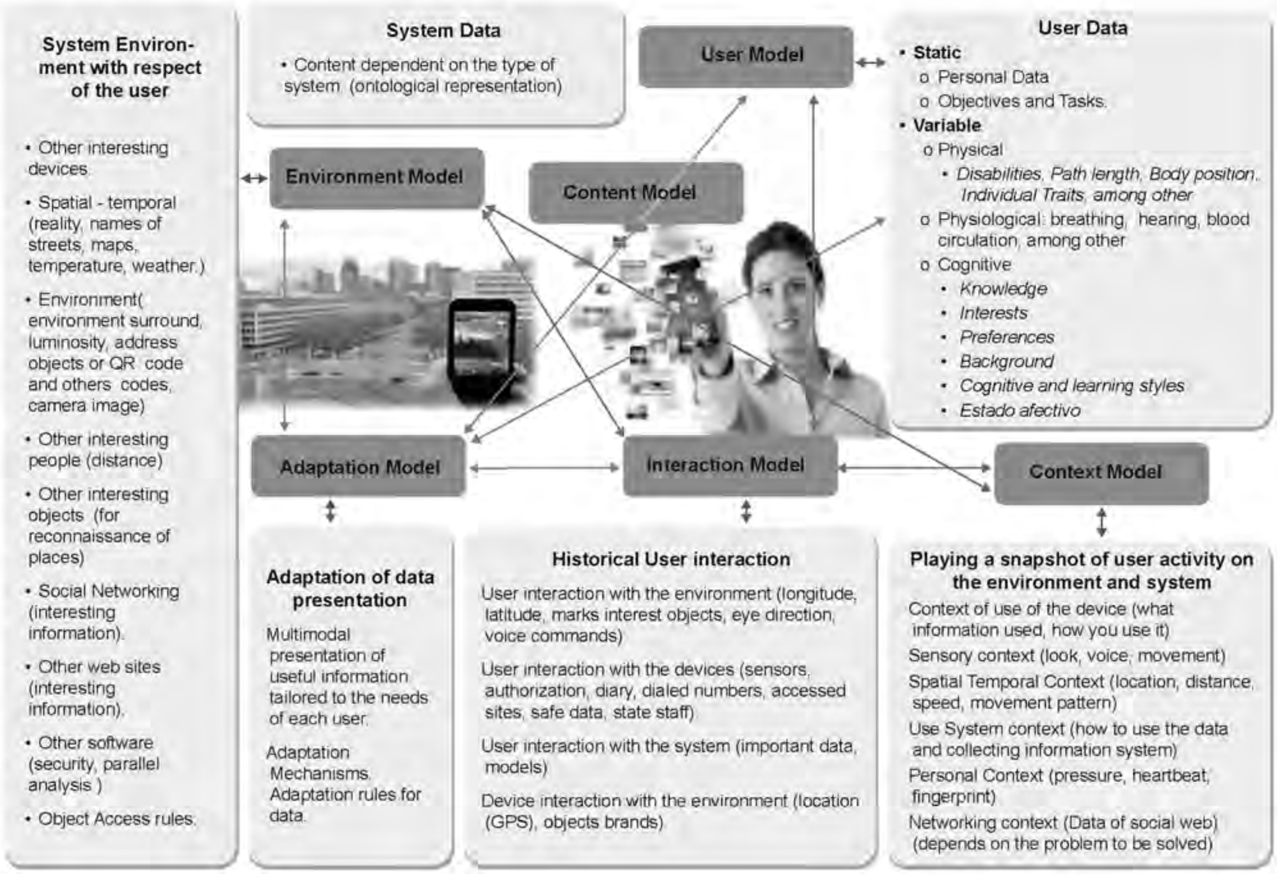

Fig. 1. Features for each A^2R Model

in which they request help for daily activities. It would augment their quality of life and help them maintain their autonomy.

All of these applications require an ontological model, described in OWL, which specifies the following four ontologies:

- User ontology: this refers to a user model in which the users personal characteristics are represented, what the user wants to do and what she or he is doing, as well as social connections.
- Device ontology: This is a formal description of the pertinent devices and their characteristics.
- Physical environment ontology: including spatial distribution, object models and their physical relationships.
- Service ontology: this specifies the contextual model of specified applications and services that users can access. These have an AR interface.

This work concludes that ontologies together with reasoning techniques allow the A^2R systems to:

- Reduce ambiguity in contextual data in order to improve data quality.
- Determine what data should be displayed to the user by evaluating explicit data about the users situation and preferences.
- Infer anticipated data using reasoning techniques.

A. Analysis of other relevant ontologies

Even if the use of ontologies in A^2R systems is quite recent, some ontological models of users and environments have been previously developed in the context of adaptive and ubiquitous systems. It is the aim of this work to describe the most relevant existing ontologies that have been found and to compare them with the requirements imposed by our definition of A^2R models, in order to determine their suitability and coverage.

- **GUMO** (General User Model Ontology): Expressed in the OWL language, GUMO supports the representation of user models. In this ontology the information is modelled in terms of user model dimensions. A user model dimension is divided into three parts: Auxiliary, Predicate and range [16], e.g the users low interest in football would be represented by the Auxiliary "has interest", the Predicate "football" and the Range "low" [17]. After its creation, this ontology was included into the UbisWord Ontology (see below).

- **SUMO** (Suggested Upper Merged Ontology)[1]: SUMO is the only formal ontology that has been mapped to all of the WordNet lexicon. SUMO is written in SUO-KIF language, but a translation to OWL is available. It is free and owned by the IEEE [2]. Part of this ontology has also been included into the UbisWorld Ontology. It provides a very wide vocabulary to describe information in many different domains. It is not specifically intended for user modelling, but it can be very useful to build other A^2R models such as the content model, the environment model, etc.
- **Ubisworld** [3]: It represents parts of the real world, like an office, a shop, a museum, an airport or a city. It represents persons, objects, locations as well as time events and their properties and features. It is available in OWL. The knowledge about concepts, individuals and relations in UbisWorld is modelled by means of two ontologies: GUMO and the Ubis Ontology [4]

Given that Ubisworld is the most complete ontology found for ubiquitous systems, we thought that it would be worth checking to which extent Ubisworld covers the needs of A^2R. To this end, we have created the following table I in which we show how Ubisworld models the different types of information required by our proposed models. We have not included the adaptation model in the table because the best language for the formalization of this model does not seem to be an ontology, but rather rules or algorithms. We have not included the content model in the table either, since this model is the most domain dependent and therefore a generic ontology hardly may cover the needs of any application.

Apparently, the table I shows that Ubisworld provides a quite good coverage of the needs of A^2R, although with some significant gaps, such as the lack of support for the representation of the user's sensorial context (what the user is looking at, hearing or touching), and the lack of proper constructs for the representation of the Interaction Model. Moreover, Ubisworld internal structure does not map easily into the models that we have proposed for A^2R, with some related information spread over different classes, which harms its adoption as the basic information infrastructure to support the design and development of A^2R applications and their maintainability. Moreover, when examining the OWL version of Ubisworld, we can see that just a few properties are defined and key auxiliaries such as hasDone or hasKnowledge are defined as OWL classes and not as relations among classes. These features of the OWL version make the adoption of Ubisworld in A^2R applications very difficult.

VI. Conclusion

Adaptive Web systems are examples of successful application of adaptability, both to users interests and to their real-time context. Although some efforts have been made to develop Adaptive Augmented Reality, this technology has not yet equaled the adaptability levels achieved by web systems.

One of the reasons for this primitive state in adaptability might be that the development of a A^2R is still a very complex endeavour, encompassing many technological challenges, without clear and specific process models and methodological and architectural guidelines to lead the development process, and with still too simple development tools.

We aim at the definition of an architectural model for A^2R systems which is structured around a basic set of models for A^2R applications which are inspired in models coming from adaptive web systems. After an initial identification of the basic content to be maintained by each model in the architecture, we have checked to which extent state of the art ontologies cover the needs of information in A^2R. As a conclusion of this analysis, we can affirm that although state of the art ontologies, and more precisely, Ubisworld, contain most of the information elements required by A^2R, the structure of these ontologies is not the most appropriate for supporting the development of A^2R applications.

To the best our knowledge, there is just one work that addresses the development of A^2R models by using ontologies. This work manages to demonstrate that rules represent a good approach to define the adaptation model and to update A^2R models formalized with ontologies. On the other hand, we think that there is still much work to be done regarding alternative approaches to define the adaptation model and the update mechanisms associated to the models.

VII. Lines of Research

Based on our conclusions, we have identified the following lines of research for A^2R technology:

1) *Formalize the models using ontologies in widely accepted languages like OWL and applying knowledge engineering good practices.*
2) *Define the means for initializing and updating the models.* Identify data sources within the environment and context.
3) *Specify how the adaptation model selects content* to be presented to the user. To develop customized adaptations in real-time, we need to:
    - Research and define *potential components of the adaptation model that recognize changes in interest,* starting from the user and context models and taking into account the environment and user interactions.
    - Investigate *how the adaptation model proposes new content* by drawing on data from the content model, recognizing changes in the environment and interests from the user model, and interpreting the real-time context and user interactions with it.
    - Define *how the adaptation model defines the content presentation* mode through its multimodal interface. The model should take into consideration the specifics of each device and the users preferences.

[1] http://www.adampease.org/OP/
[2] http://www.adampease.org/OP/
[3] http://www.ubisworld.org/
[4] http://ubisworld.org/index.php

Model	Characteristics proposed (specified in the figure 1)	Ubisworld
User Model	• Static: – Personal Data	• Basic User Dimensions (GUMO): Contact Information, Demographics, Abilities, Personality, Characteristics, Emotional States, Role, Nutrition, Relationships, Basic Human Needs
	• Static: Objective and task	• Situational: Other Dimensions (GUMO): hasPlan, hasGoal
	• Variable: – Physical: Disabilities, Path length, Body position, Among others – Physiological: Breathing, Hearing, Blood Circulation, Among others	• Basic User Dimension (GUMO): Motion, Mood, Facial Expression • Basic User Dimension (GUMO): Physiological state
	• Variable: – Cognitive: Knowledge, Interests, Preferences, Learning styles	• Domain Dependent Dimensions (GUMO): Interest, Knowledge, Preference • Situational: Other Dimensions (GUMO): hasInterest, hasBelief, hasknowledge, hasPreference
Context Model	• Context of device use	• Context sensor dimensions (GUMO): Sensor Dimensions
	• Sensorial context	
	• Spatio Temporal Context	• Context Dimensions (GUMO): Location, Physical Environment • Situational: Other Dimensions (GUMO): hasLocation
	• Context of System Use	
	• Personal Context	• Basic User Dimension (GUMO): Motion, Mood, Facial Expression • Basic User Dimension (GUMO): Physiological state
	• Social Networking Context	

Continued on next page

<table>
<tr><th>Model</th><th>Characteristics proposed (specified in the figure 1)</th><th>Ubisworld</th></tr>
<tr><td>Interaction Model</td><td>User Interactions with the environment
User Interaction with the devices
User Interactions with the system
Device Interations with the environment</td><td>Situational; Other Dimensions (GUMO): hasProperty, hasRegularity, hasDone, hasRated, IsRated, HasExperience, isTagged, hasask</td></tr>
<tr><td rowspan="4">Environment Model</td><td>Spatio temporal</td><td>Spatial Elements(UbisWorld):
Location (Continent, Country, Region, City, Quarter, Street, Place, Building, Floor, section, Room)
Spacial Purpose (shopping, Gastronomy, Leisure, Education, Sports and Fitness, Entertainment, Retail Brand, Public transport)
Spatial Relation (Has Inclusion, has Connection, Has Mapping, nearest parking, HasPurpose, nearest Bus Stop, nearestTrainStation, nearestAirport)</td></tr>
<tr><td>Other interesting objects
Other interesting devices</td><td>Physical Elements (UbisWorld)
Being (Person, Pet, Company, Plant)
Thing (Device, Furniture, Vehicle, Other object, Media, Home Appliance, Building)
SUPIE Products (digital camera, food, mobile phone, musicPlayer, pda, speech dictation, speech synthesizer)</td></tr>
<tr><td>Other Interesting people</td><td>Physical Elements (UbisWorld)
Being (Person)</td></tr>
<tr><td>Social network</td><td>Context Dimensions (GUMO): Social Environment</td></tr>
</table>

TABLE I: Mapping from A^2R models to UbisWorld ontologies

4) Evaluate *how the context model interprets user activities*, so that data are validated at the instant when the data are adapted in real-time.
5) Undertake a comprehensive evaluation of both the models and their attributes and the level of adaptability achieved. The goal is to identify and assess the advantages and benefits delivered at the moment when the user interacts with both specific and general contexts within the A^2R system.
6) Define a formal, systematic, and general process for the analysis and design of A^2R systems. These systems can then be customized to solve specific problems. Essential guidelines for adaptation and evaluation must be included, so that prior contributions add to the systematized design of the A^2R system.

REFERENCES

[1] R. T. Azuma *et al.*, "A survey of augmented reality," *Presence*, vol. 6, no. 4, pp. 355–385, 1997.

[2] A. Damala, N. Stojanovic, T. Schuchert, J. Moragues, A. Cabrera, and K. Gilleade, "Adaptive augmented reality for cultural heritage: Artsense project," in *Progress in Cultural Heritage Preservation*. Springer, 2012, pp. 746–755.

[3] J. A. Neuhöfer, F. Govaers, H. El Mokni, and T. Alexander, "Adaptive information design for outdoor augmented reality." *Work (Reading, Mass.)*, vol. 41, pp. 2187–2194, 2011.

[4] S. Oh and Y.-C. Byun, "A user-adaptive augmented reality system in mobile computing environment," in *Software and network engineering*. Springer, 2012, pp. 41–53.

[5] A. C. Martins, L. Faria, C. V. De Carvalho, and E. Carrapatoso, "User modeling in adaptive hypermedia educational systems," *Journal of Educational Technology & Society*, vol. 11, no. 1, pp. 194–207, 2008.

[6] D. Benyon and D. Murray, "Adaptive systems: From intelligent tutoring to autonomous agents," *Knowledge-Based Systems*, vol. 6, no. 4, pp. 197–219, 1993.

[7] P. Brusilovsky and E. Millán, "User models for adaptive hypermedia and adaptive educational systems," in *The adaptive web*. Springer-Verlag, 2007, pp. 3–53.

[8] A. Kobsa, "Generic user modeling systems," *User modeling and user-adapted interaction*, vol. 11, no. 1-2, pp. 49–63, 2001.

[9] P. Brusilovsky, "User modeling and user-adapted interaction," in *Adaptive Hypermedia*, vol. 11, no. 1-2, 2001, pp. 87–110.

[10] E. Popescu, C. Badica, and P. Trigano, "Rules for learner modeling and adaptation provisioning in an educational hypermedia system," in *synasc*. IEEE, 2007, pp. 492–499.

[11] A. Bunt, G. Carenini, and C. Conati, "Adaptive content presentation for the web," in *The adaptive web*. Springer, 2007, pp. 409–432.

[12] P. L. Heufemann, J. G. Villegas, and I.-Y. Ko, "Web usage based adaptive systems," in *Advanced Techniques in Web Intelligence-2*. Springer, 2013, pp. 127–148.

[13] P. Brusilovsky, "Methods and techniques of adaptive hypermedia," *User modeling and user-adapted interaction*, vol. 6, no. 2-3, pp. 87–129, 1996.

[14] A. U. Frank, *Ontology for spatio-temporal databases*. Springer, 2003.

[15] R. Hervás, J. Bravo, J. Fontecha, and V. Villarreal, "Achieving adaptive augmented reality through ontological context-awareness applied to aal scenarios." *J. UCS*, vol. 19, no. 9, pp. 1334–1349, 2013.

[16] D. Heckmann, T. Schwartz, B. Brandherm, M. Schmitz, and M. von Wilamowitz-Moellendorff, "Gumo–the general user model ontology," in *User modeling 2005*. Springer, 2005, pp. 428–432.

[17] D. Heckmann, *Ubiquitous user modeling*. IOS Press, 2006, vol. 297.