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Semantic Description of Multimodal Devices: Modelling and Evaluation

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Abstract: The heterogeneous, dynamic nature of current communication environments necessitates that all system components that form part of a personalisation framework should be context aware. To ensure context enabled interoperation, a shared, formalised specification of devices and services in the ambient environment is a must. With this aim, this paper presents an ontology model that captures the semantics of the multimodal devices and services in the mobile ad-hoc environment. The approach is validated using available metrics and compared to existing approaches, both through subjective feature-based evaluation and metrics' calculations. This paper also extends the metrics' usability by extending the analysis to interoperability with application logic and domain capture.

Keywords: Ontology, semantic device description, evaluation, ubiquitous environments.

1. Introduction

Advances in mobile and wireless access technologies and the parallel rise in the use of devices interconnected with such mechanisms have brought the pervasive environment concept closer to fruition. Personalisation in such smart spaces necessitates the development of intelligent enabling frameworks. Such a framework should probe the ambient environment for available multimodal interfaces for user interaction, analyse these and deliver relevant services. To this end, a description of the multimodal device capabilities at a semantic level is a crucial component for delivering services with the best possible combination of modalities to the user.

With devices of diverse capabilities existing in the environment (from printers to smartphones), flexibility and expressiveness are two characteristics required in the description model. Ontology models can express detailed semantic information about services, devices and the ambient environment. Ontology includes machine-interpretable definitions of basic concepts in the domain. Of particular interest to our problem domain is the OWL Web Ontology language, which is the emerging standard representation language for ontologies, and as such has good tool support [1].

With the given ontology model in place, it is imperative to asses if it conveys the particular vocabulary's intended meaning. Available evaluation methods include those that are subjective and others that are applicable to a particular ontology structure [2]. In addition to subjective feature evaluation, it is important to identify metrics that give an indication of ontology complexity and optimum structure. Ontology complexity measurements can give an indication of how well the ontology model integrates with other software components, for instance, query mechanisms.

2. Objectives

This paper presents an ontology model that aims to define a concept that successfully captures the semantics of the various services available in the ambient mobile ad-hoc environment and models it in a way that makes it amenable for applications to query and discover available services. The objective is to design a semantic context model that captures all the important features of multimodal aspects by defining a logical categorisation of major concepts (or classes), sub-concepts and to recognise the relationships that could exist between these.

The defined model is then compared to existing device ontologies in terms of features captured and also other available evaluation metrics. The paper also identifies a suite of metrics from current state of the art and analyses them to assess the ontology models in terms of complexity, relationship diversity and concept aggregation.

3. Related Work

There have been several efforts in the research community to describe the capabilities of devices with ontology based models, including the FIPA (Foundation for Intelligent Physical Agents) specification [3] for device ontology. It builds upon some of the CC/PP (Composite Capability/Preference Profiles) concepts and defines a device ontology to model the static device characteristics as well as the hardware and software agents provided on the device. It is intended to facilitate agent communication for content adaptation. However, as pointed out in [4], the model can accommodate only terminal devices and does not facilitate effective description of devices such as printers and scanners. The device ontology proposed in [4] organises information in five classes: device description, hardware, software, device status and service. Though a sample characterisation is provided for printers, the general categorisation for hardware and software categories is not provided. Another partial structure of a device ontology as part of a context management framework is provided in [5]. The device information includes ID, language, interface definition and resolution.

4. Methodology

A multimodal device ontology should provide clear links between the software elements and the physical device description. The software elements encompass information to differentiate between similar service offerings, for instance, supported file formats. For a service ontology, three levels can provide a complete view of service description: the static properties (e.g. type, provider), its dynamic properties (its behaviour) and its interface (parameters, methods) [6]. The physical hardware categorisation adds another layer of refinement on top of this, which could also function as a constraint mechanism during service selection and delivery.

Figure 1 shows the partial structure of the device domain ontology discussed in this paper.

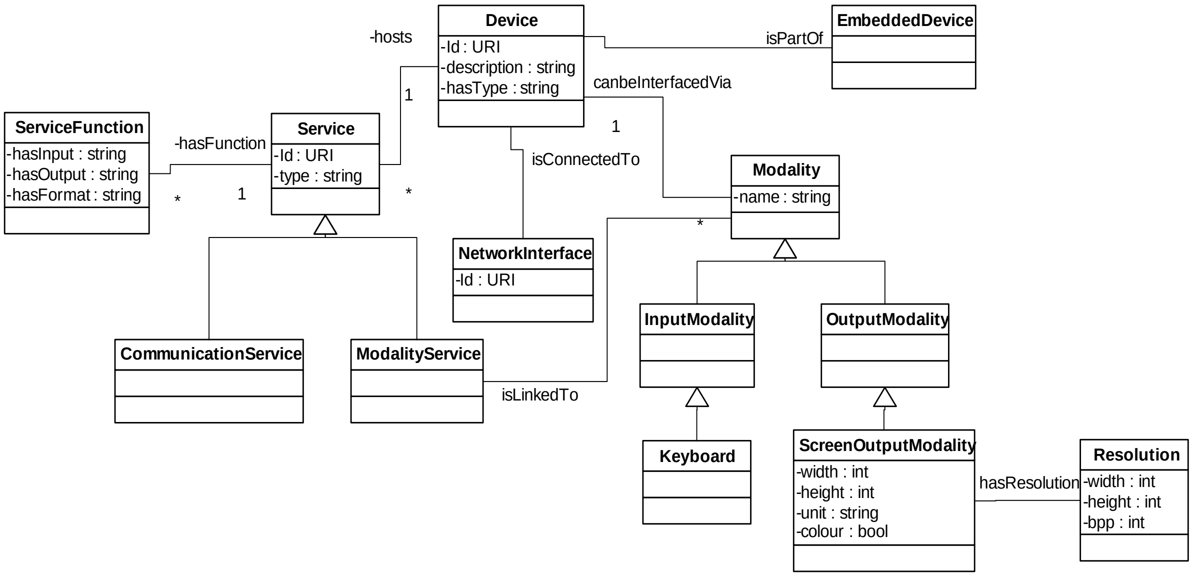

Figure 1: Structure of Domain Ontology

The defined ontology includes the static properties, for instance, the user interface, network interface and other input/output modalities. In addition, the service description concepts are modelled to capture the service behaviour and link the services to the static device modalities. The asserted relationships model the logical relations between the different classes.

The Device class is linked to the Modality, Service and NetworkInterface classes. To model the scenario where a physical device could have independent constituent components, such as a mobile phone with screen, keypad etc., the EmbeddedDevice class inherits all the properties of the Device class and introduces the object property, 'partOf', to identify the link to the parent device. The Modality class is sub-classed into Input and OutputModality, i.e. $InputModality \subseteq Modality$ and $OutputModality \subseteq Modality$, with further refinements based on the various types of modalities possible. For instance, the ScreenOutputModality has data type properties specifying its height, width, colour capability and links to the Resolution class for describing the screen resolution in terms of horizontal and vertical resolution in bits per pixel. The Service class has categories for services directly describing devices modalities or those providing other services (e.g. content storage). The ModalityService class thus links to the Modality class. The ServiceFunction is defined in terms of the service input, output and formats to model the service behaviour as a function between input and outputs.

Another ontology that concerns the related domain of service description is the DAML ontology (http://daml.umbc.edu/ontologies/dreggie-ont.owl) which forms part of the DReggie [7] semantic service discovery framework. It describes m-commerce services in terms of their functionality, capability, platform requirements and other attributes. The service component class is the root, with capability and functionality descriptions added as properties. Memory and CPU requirements are considered, though network interfaces are not factored in.

5. Applications

The proposed multimodal ontology forms part of a Personal Assistant Agent (PAA) [8] framework that aims to facilitate context sensitive service provisioning in ubiquitous environments. The technical scenario of the functioning of the framework is presented through a statechart in Figure 2.

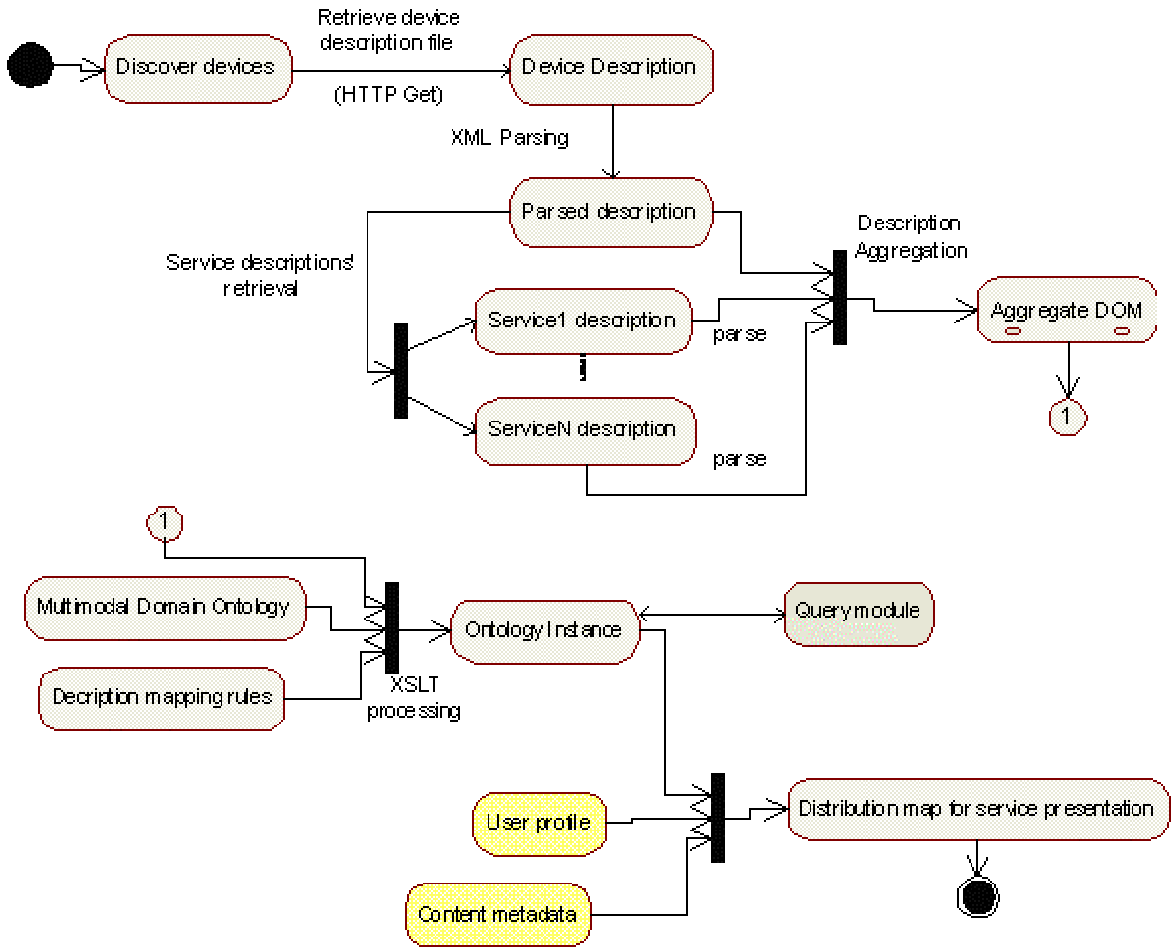

Figure 2: Multimodal Ontology Application StateChart

Multimodal devices in the ambient environment are discovered by a discovery module. In an example use case, the UPnP protocol [9] is used for this step. The descriptions, which consist of device descriptions and hosted software services' descriptions are retrieved by HTTP GET commands. The XML description files are parsed into a DOM (Document Object Model) that converts the XML structure into a tree of nodes in memory and provides interfaces for access and modification. Mapping rules then transform the DOM structure to an OWL ontology instance with reference to the proposed multimodal domain ontology. This is done using XSLT (Extensible Stylesheet Language Transformations). Thus, the ambient environment description based on the developed ontology constitutes the input to a reasoning subsystem that implements a rule based mechanism for matching content metadata and stored user preferences to available device modalities. The output of this reasoning engine shows the best possible modality combination for content presentation to the user.

The ontology formalism also enables semantic querying of the reasoned output. For instance, device capabilities can be queried either by hardware instances (screen availability) or available services (text output), as illustrated by the results shown in [10].

A demonstrator is currently under development for the project [11] of which this work is a part of. This work also fits as an input to adaptation systems [12] developed in this project.

6. Technology Description

The evaluation procedure includes ontology content evaluation as well as a structure-based evaluation that is based on statistics and graph theory. Structural evaluation approximates the ontology structure as a directed acyclic graph, with each node representing a concept and the directed arcs denoting the relationships between them.

The defined metrics analyse the ontology model from different dimensions to provide an evaluation of its structure and alignment to the domain knowledge internal structure. The first defined metric, Property Standard Deviation (PSD), proposed in [13], deals with the distribution of relations amongst the concepts of the ontology. There are two types of properties in ontology: object and datatype property. Since it is the object property that reflects the relations between instances of two classes, it is used to describe the connections in the ontology. Equation (1) depicts the calculation of PSD:

$$PSD = \sqrt{\frac{\sum_{i=1}^{n}(C_i - PE)^2}{n}} \qquad (1)$$

where C_i is the count of the object properties of the *ith* concept, n is the total number of concepts and PE is the property expectation, given by

$$PE = \frac{\sum_{i=1}^{n} C_i}{n} \qquad (2)$$

Obviously, the higher the PSD, the more uneven the distribution.

The Concept Connectivity (CC) metric gives a measure of the connectivity between the various defined concepts. The ontology can be regarded as an undirected graph $G = \langle V, E \rangle$, with each concept being a vertex in this graph. If a concept has an object property whose value is an instance of another concept, an edge will be drawn between these two concepts. After the whole undirected graph has been created, the number of connectivity branches is calculated.

With the Concept Connectivity metric giving an indication of the width of the ontology, the next two defined metrics consider the height factor. The path-length related metrics, documented in [14], consider only inheritance relationships, such as 'is-a' or 'part-of'. Here, a path is defined as a distinct trace from any given concept to the root. λ_i denotes the longest path length of concept N_i in an ontology of n concepts and is given by

$$\lambda_i = \max(pl_{i,k}), 1 \le k \le p_i \qquad (3)$$

where $pl_{i,k}$ is the set of path lengths for concept N_i.

The max path length of the ontology (Λ) is equal to the longest λ_i; defined by

$$\Lambda = \max(\lambda_i), 1 \le i \le n \qquad (4)$$

$\overline{\Lambda}$, the average path-length metric is calculated using

$$\overline{\Lambda} = \sum_{i=1, j=1}^{n, p_n} pl_{i,j} \Big/ \sum_{i=1}^{n} p_i \qquad (5)$$

These two metrics give an indication of the semantic scope of the ontology by measuring the extension to the most general concept or root.

$\sigma = \Lambda / \overline{\Lambda}$ examines the concept aggregation factor. A σ value of less than 2 means that most concepts surround the root, depicting high concept coherence. A value of more than 2 denotes a loose concept organisation.

7. Results

The evaluation of the domain ontology introduced in this paper has been done both subjectively and with the identified structure-based metrics suite. At a first instance, the defined ontology has been compared with the DReggie ontology, on the basis of domain features captured. This evaluates the ontology content and helps to assess the ontology capability of conveying the given vocabulary's intended meaning. Table 1 shows the results of this subjective evaluation.

Table 1: Subjective evaluation results for multimodal domain ontology

Feature	Multimodal ontology	DReggie ontology
Capability description	√	√
Physical requirements – Service demarcation	√	×
Network interface	√	×
Service formats	√	×
Service cost	×	√
Service properties	√	√
Service inputs and outputs	√	√
Input, output modalities	√	×

The structure-based evaluation focuses on the internal structure of ontology. Table 2 summarises the results of the metrics' (defined in the preceding section) calculation for the two ontologies.

Table 2: Structural evaluation results for multimodal domain ontology

Ontology	PE	PSD	CC	Max path length (Λ)	Avg. path length ($\overline{\Lambda}$)	Concept aggregation (σ)
Multimodal ontology	1.46	0.81	9	3	2.04	1.47
DReggie ontology	1.78	1.42	23	2	1.07	1.87

8. Discussion

As already pointed out in this paper, a multimodal device environment is best described at two different planes: physical hardware description and associated software services interface modelling. To this end, the here discussed ontology models a clear demarcation between these two concepts, while maintaining a comprehensive description of each. It also takes into account the service description requirements outlined in [6]. While the hardware-software decoupling is also apparent in the ontology framework in [4], it suggests separate ontologies for describing devices and services.

This paper, however, proposes that these two concepts should be part of the same ontology. This ensures that the ontology instance populated with real-world data of devices in the ambient environment can be directly input to reasoning subsystems, with all the information being available in one file. Also, this does away with ontology alignment and merging requirements, which would be necessary if the information were to be distributed across different ontologies.

A feature comparison with the complete, publicly available DReggie ontology shows that the here discussed ontology captures the multimodal device domain better. The FIPA standardisation effort for device ontologies is, at a first instance, a frame-based ontology and is aimed at agent communication. From an implementation standpoint of ontology content evaluation, there are important connections between the components used to build the domain ontology (concepts, relations, properties); the knowledge representation used to formalize these components (frames, description logic (DL), first order logic etc.) and the languages used for implementation (with frames, DL in several frames or DL languages). This is so because different KR (knowledge representation) paradigms offer different reasoning mechanisms that can be employed for content evaluation [15]. The proposed ontology is modelled in OWL-DL and thus, implicitly benefits from the DL classifiers to derive concept satisfiability and consistency.

To derive a picture of ontology complexity from its structural organisation, this paper utilises metrics available from current state of the art. These are used to validate the ontology proposed while also comparing it with other published efforts. Moreover, this paper extends the metrics' usability by extending the analysis to interoperability with application logic and domain capture. For instance, this paper analyses how the ontology can perform together with a query application, based on the metric calculations. The related state of the art only theoretically evaluates the ontologies using these metrics [13] or utilises them for ontology evolution tracking [14] and does not relate it to application logic.

From the numbers in table 2, it is apparent that the average relation among concepts is almost similar in both ontologies (PE value comparison). However, our ontology shows the most even distribution of these concepts, as shown from PSD values. The maximum and average path length metrics in unison provide a picture of the ontology depth and by extension, the detail with which concepts are covered. The low value of $\overline{\Lambda}$ (~1) for the DReggie ontology implies that it is essentially a flat structure with most concepts defined very near to the root. Actually, a look at the ontology structure, drawn as a directed acyclic graph, shows that most classes are defined at the same level below the most general concept (owl: Thing) and only 1 concept demonstrates any subsumption relationship. This illustrates that our defined ontology covers the domain in a more detailed manner due to its higher schema depth, while the DReggie ontology depicts general knowledge with a low level of detail. This fact is borne out by the feature evaluation results in table 1. The flat structure of the DReggie ontology is also evident with its large value of CC when compared to its total number of concepts (n); where n=14 for DReggie and n=24 for device ontology. Since both ontologies have σ values less than 2, this means that the concept organization and aggregation is high. A σ value above 2 signifies loose organisation. This also has implication for the intended use of the ontology. Since the low σ value signifies that the concepts tightly surround the root, path traversals can be minimised, i.e. the distance from the most general to the most specific concept is not great. This can help speed up query answering and concept search. Overall, the multimodal domain ontology has a good representation in terms of property and connectivity.

9. Conclusions

The multimodal ontology described in this paper provides a framework for describing devices and services in a formal structure amenable to automated reasoning and effective query procedures. The presented suite of metrics offers an evaluation framework that evaluates ontology models from a plurality of dimensions. An analysis of the identified metrics gives a clear picture of ontology structure and complexity. For instance, the concept aggregation metric can give an indication of output performance when the ontology is plugged into a query mechanism, with higher values translating to longer times to get to any particular concept from the root.

The evaluation figures reveal that the here discussed domain ontology performs well both in terms of property and connectivity properties.

For a more comprehensive evaluation, the other researched device ontologies should be publicly available.

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