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Ontology-based Searching Framework for Digital Shapes

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Abstract. Knowledge related to Shape Modelling is multi-faceted because of the complexity and heterogeneity of the involved resources and because different applications may cast different semantics on them. A fast evolution of the field is now conditioned by how research teams will be able to communicate and share resources and knowledge. The field needs to be formalized in order to achieve a shared conceptualization accessible by the whole scientific community and eventually to ensure an actual exploitation of its knowledge within the Semantic Web. In this context, the main objective of the Network of Excellence AIM@SHAPE is twofold: on the one hand to devise tools to capture the implicit semantics of digital shapes, and on the other hand to encode and formalize the domain knowledge into context-dependent ontologies. The paper describes the first results in the direction of developing an ontology for shape acquisition and reconstruction and its effective use in the Digital Shape Workbench, a searching framework for sharing resources (shapes, tools and publications) and their related knowledge.

1 Introduction

The success of the scientific enterprise largely depends on the ability of sharing scientific resources (information, papers, tools) among the scientific community. In the last decade the web has been emerging as a mean to fulfil this requirement by facilitating the communication and by making easily available a huge amount of information. This problem is particularly relevant in the field of Shape Modelling, which concerns methods to represent, create, process and analyse digital representations of objects for a variety of applications. The most typical kind of resources in this field are *digital shapes*, i.e. multi-dimensional media characterized by a visual appearance in a space of 2, 3, or more dimensions. Examples of shapes are pictures, images, 3D models, videos (disregarding the sound track), animations, etc.

Shape Modelling includes Computer Graphics and Vision and it is based on a large spectrum of fundamental domains, including differential geometry, numerical analysis, computational geometry and discrete topology. Recently, the field has reached a state where each individual fundamental domain is well understood and exploited. A fast evolution of the field is now conditioned by how research teams will be able to inter-communicate. Beside the need of an *e*-science platform for supporting research in the field, shapes are gaining importance in different social contexts. Considering that most PCs connected to the Internet are now equipped with high-performance 3D graphics hardware, it seems clear that in the near future 3D data will represent a huge amount of traffic and data stored in the Internet. It has been predicted that geometry is poised to become the *fourth wave* of digital multimedia communication, where the first three waves were sounds in the 70's, images in the 80's, and videos in the 90's. Digital shapes are therefore expected to take a central role in the Semantic Web in the coming years, with high potential impact in several key areas.

In this context, the Network of Excellence AIM@SHAPE [1] is pursuing the introduction of Knowledge Management techniques in Shape Modelling, with the aim of making explicit and sharable the knowledge embedded in digital shapes. On the one hand, this requires the development of tools able to extract semantics from 3D models (e.g. automatic or semi-automatic annotation tools), on the other hand it is necessary to build a common framework for reasoning, searching and interacting with the semantic content related to the knowledge domain. As pointed out by Hendler [2] researchers may need to find and explore results at different levels of granularity, from other perspectives in the field or from a complete different scientific field. Although scientists are relying on the web to share their own scientific resources, the current Web technology is clearly insufficient for the need of supporting collaborative e-science. In AIM@SHAPE the Digital Shape Workbench (DSW, for short) is a more elaborated framework to store shapes, tools, publications along with the knowledge related to them, relying on a search engine able to provide significant results. The development of the DSW for the complex field of Shape Modelling requires the conceptualisation of the domains and the precise characterization of the resources. The AIM@SHAPE effort can be seen as a step towards contributing to the goal of the Semantic Web itself. As a matter of fact, the success of the Semantic Web as the mean to share scientific resources is significantly limited, if a shared conceptualisation of scientific fields will not emerge.

The paper aims at presenting the contribution of AIM@SHAPE to the harmonization of content in the field of Shape Modelling. The complexity and the wideness of the domain makes unreasonable to provide a shared conceptualisation in terms of one monolithic ontology, and it forces in building a framework where different ontologies are adopted to represent facets of specific domain applications and usage scenarios. In particular, the paper presents fragments of an ontology which formalises the knowledge related to the pipeline of Acquisition and Reconstruction of digital shapes. The paper will briefly review the status of the tools needed to build a semantic-based platform for Shape Modelling. Then, the AIM@SHAPE approach of modelling the semantics of digital shapes and shape resources will be introduced and a detailed description of the acquisition phase of a shape will be given. Finally, the DSW search architecture will be briefly sketched, and conclusions will be drawn.

2 Related Works

While academic and research communities have historically been key contributors to the development of the Internet, the potential of Internet as a tool for collaborative research activity have been only recently understood. In the field of Shape Modeling, the use of Internet as a mean for collaborative environment has been mainly focused on setting up benchmarking for testing the performance of different algorithms. The most famous example is the Stanford Repository [3], a collection of downloadable models obtained by scanning, documented by rather simple attributes. The site is a simple HTML page, with limited search capabilities.

The retrieval of digital shapes in large heterogeneous repositories is still a complex task. Information encoded in multi-dimensional media, unlike text data, is totally *implicit*, being based on data formats that have no relation with data interpretation and offer no grasp to their direct access and easy understanding. Browsing, retrieving and navigating efficiently in video or image databases is not easy at all, not to mention databases of 3D shapes and data volumes. At the state-of-the-art, the only effective means to perform context-based retrieval on such databases rely on textual annotations of media (e.g. keywords), which are inserted manually and constitute only a negligible portion of the information stored in the repository. In the last years, there has been quite a lot of effort in the Shape Modelling community for providing smart tools able to retrieve three-dimensional data using shape matching [3]. These engines address the problem in a geometric sense, so they are able, at a certain extent, to retrieve objects that present some geometric similarity. The peculiarities of the field make the general problem of retrieving intrinsically complex. The knowledge is not solely carried by digital shapes, but also by hardware and software tools used to acquire and transform them. Moreover, shapes are heterogeneous, as they can be represented in different ways with regard to both format and content. Being multi-dimensional data, the size of digital shapes is generally very big: for accurate 3D models, the size can be some GigaBytes each. Last but not least, shapes are used in different environments such as: Industrial Design (e.g., CAD models of products,), Cultural Heritage, Medical Applications (e.g., tomography), Entertainment (e.g., computer animations), Geographical Information Systems (e.g., three-dimensional models of terrains), and many more.

The support of querying facilities has always been a primary requirement for repositories of any kind. Of course, the simplest approach is to search for keywords in filenames, captions, or context. However, this approach is highly inefficient. Moreover, the current digital shapes repositories are centered on the geometric aspect of shapes, and not on the knowledge they represent. Different methods for measuring similarity between shapes have been presented [4], [5]. Content-based retrieval and classification systems have also been developed for other multimedia data types, including audio [6], images [7], and video [8]. The representation of a shape can be sorted according to three levels of sophistication: the Geometric level, the Structural level and the Semantic level. While on the geometric and structural level there are numerous approaches, at the semantic level very little work has been done until now. In the last few years, apart from the AIM@SHAPE Network of Excellence [1], there has been a considerable increase of interest for techniques to extract and stream knowledge embedded into multimedia content, ranging from basic research efforts to projects seeking an integrated effort at European level [10], [11].

The proliferation of knowledge caused by the widespread use of the Web as a knowledge communication platform has posed the same and even more imperative requirements for performing queries and locating resources into the vast information space. We believe that the addition of explicit semantics can improve search. However, the data models used to represent and encode knowledge on the Web differ from the traditional data structures. RDF [12], RDFS [13] and OWL [14] are the emerging standards used to encode web-based data. Thus, the functionality a querying language should support the structure and the peculiarities of the new paradigms. Some query languages have been developed for RDF/S (e.g. RQL [15], SquishQL[16], TRIPLE[17]), and DAML (e.g. DQL [18], RDQL[19]). For querying OWL semantic web repositories, the query language OWL-QL [20] has been proposed, which is the successor of the DQL query language and takes advantage of the expressive power of the OWL language itself. OWL-QL is a language with precisely defined semantic relationships among a query, a query answer, and the knowledge base(s) used to produce the answer. Practical description logic (DL) systems such as Racer [21] offer a functional API for querying a knowledge base. The first step towards satisfying more expressive querying facilities provides the new Racer Query Language (nRQL) [22].

3 Ontology-driven Annotation of Shapes: the AIM@SHAPE Approach

Due to the intrinsic complexity of shapes, ontology-driven metadata are necessary in order to reach a sufficient level of expressiveness. Metadata should provide a thorough characterization of shapes (**Fig.1**) by storing: *(i)* the information related to its history, such as the acquisition devices and techniques for creating it or the tools for transforming it (its *past*, e.g. for documentation), *(ii)* the information intrinsically held by the shape itself (its *present*) and *(iii)* the information related to its capabilities and potential uses, such as the possible steps that can be performed or the tools that can be used (its *future*, e.g., for acquisition/process planning).

Moreover, ontology-driven metadata should be able to represent different levels of sophistication describing a shape as a *simple resource* (e.g. for cataloguing) and characterizing it according to its *geometry* (e.g. for rendering), to its *structure* (e.g. for matching and similarity), and to what it *represents* (e.g. for recognition or classification). **Fig. 2** gives an example of a digital shape and its intrinsic characteristics: it can be seen as simple resource (e.g. name and URL), or can be considered by its geometric characteristics (e.g. a set of triangles and normals). It has a structure (e.g. the skeleton of a teapot) or it can be seen a teapot composed by a handle, a spout, a body and a tip. It is important also to take into account the different environments where the shape can be used since the specific application determines relevant characteristics. For example, if the main purpose is to build a teapot, the identification of parts by which a teapot is composed is fundamental, while if the purpose is to let a robot grasp it, the localization of the handle is the only necessary task.

The existing branches of research in the field of Shape Modelling (e.g. Computer Graphics and Vision) are interested in one or more of the above mentioned characterizations, but also on the conditions and the tools to pass from one characterization to another. Notice that shapes play a central role in Shape Modelling, but they do not represent the only kind of resource that must be characterized in the common framework.

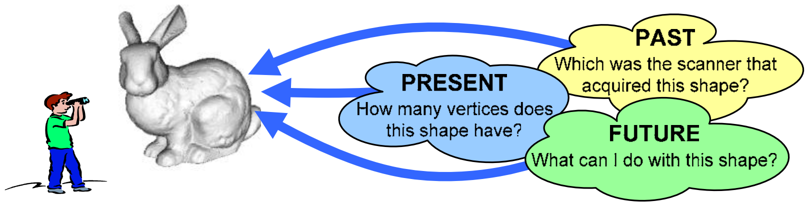

Fig. 1. An expressive characterization of a shape is made up by the information related to its history, the information intrinsically held by the shape itself and the information related to its capabilities

Everyday, scientists work with shapes, tools and publications. It is important to devise the role of these resources in the different conceptualizations, making relationships among them explicit. For example, a scientist may want to evaluate his latest implementation of a method. In this case, it is interesting to figure out which are the tools providing other implementations of the same method, the publications related to the above tools and methods, the shapes used as tests for the other implementations (e.g. for testing/benchmarking activities). It was decided to enhance the semantic aspects of shapes using two different and coexisting approaches [9]. The first strategy is *analytic* and acts on the side of Shape Modelling: development of tools and methods to extract morphological structures from low-level geometry (e.g.: find the skeleton of a shape), and semantic information from structures (e.g. trying to understand where is the handle of a door or the tip of a teapot). The second strategy is *synthetic*, and acts on the side of Knowledge Technologies: the domain knowledge and the shape semantics are encoded in context-dependent ontologies, and are used, for example, to annotate and retrieve shapes.

Concerning the synthetic strategy, three main ontologies have been initially addressed within AIM@SHAPE (Virtual Humans [23], Product Design [24] and Acquisition and Reconstruction of shapes [25]). These ontologies are used in the DSW to browse the collected resources according to context-dependent views (Section 5).

To give a flavour of what is meant by conceptualising one of the mentioned application domains, the next section describes the Acquisition and Reconstruction ontology. In particular, the fragment related to acquisition of a real object will be detailed.

4. An Ontology for Shape Acquisition and Reconstruction

The design of the ontology for Shape Acquisition and Reconstruction (AR, for short) follows mainly the *On-To-Knowledge* methodology [26] which is characterized by the specification of the requirements and an iteration of refinement, evaluation and maintenance phases. The domain of the ontology has been defined as the development, usage and sharing of hardware tools, software tools and shape data by researchers and experts in the field of acquisition and reconstruction of shapes. To specify the AR pipeline the following macro-steps have been defined: (1) *Shape Acquisition* (and Registration): the phase in which sensors capture measurements from a real object; (2) *Shaping*: the phase in which all acquired data are merged to construct a single shape; (3) *Shape Processing*: the phase in which further computations on the shape may be done (e.g. smoothing, simplification, enhancement, and so on).

As we said before, the AR ontology is intended to be targeted to the scientific community. For this reason, within AIM@SHAPE, experts of the field were interviewed to understand the requirements and to sketch the competency questions. From the feedback obtained, it was clear that an important landmark of this ontology would have been the conceptualisation of the *Acquisition Session*, with the main aims of planning the acquisition of real objects and of annotating the shapes by documenting their acquisition.

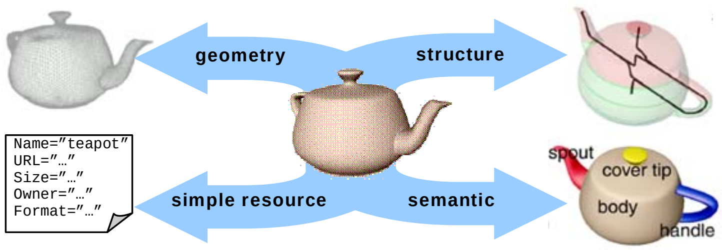

Fig. 2. A shape is described as a simple resource, or by its geometry, its structure, its semantics, depending on the application domain

Besides, it is important to remind that a proper conceptualization of shapes, tools, and publications is fundamental not only for their own characterization but also to provide meaningful cross-correlations. Nevertheless, in the next subsection we will mainly focus on the Acquisition Session, which represents a fragment of the overall ontology, as a significant example to demonstrate why our ontology can be used for gathering the resources and the related knowledge.

4.1 Modelling the Knowledge of Shape Acquisition

The *AcquisitionSession* has been modelled as a concept in the AR ontology. It is related to an *AcquisitionSystem* (which is made up by one or more *AcquisitionDevices*, e.g. scanners) and to the conditions in which the acquisition is performed: the *LogisticConditions* (they include the presence of lights, if there exist any obstacle between the real object and the scanning device and so on) and the *EnvironmentConditions* (which include the information on where the real object is –indoor or outdoor or underwater- or the level of humidity or even the weather). Moreover, some attributes are directly related to the *AcquisitionSession* (e.g. the price for renting the technological devices), while other are related to the different entities in the framework (e.g. the price of a scanning system, or the person/institute responsible for it). An overview on the conceptualisation of the Acquisition Session is given in **Fig. 3** where each rectangle represents a concept. The rows in each concept represent a slot which can be either an attribute or a relationship. For each attribute the type is specified, while for each relationship it is indicated the range. Whenever a symbol '*****'appears close to the name of an attribute or a relationship, the multiplicity can be more than 1.

An *AcquisitionSession* basically documents the acquisition of a *RealObject* and the production of a *ShapeData* (a digital shape), using a particular *AcquisitionSystem*.

ShapeData has been also modelled as a concept in our ontology, with some properties, such as its format or its URL, but also the information on the source from which it has been generated (through the slot *hasSource*). Taken the ontology fragment related to *AcquisitionSession* and *ShapeData* as an example, it can be shown that our ontology is able to support in obtaining the knowledge associated to a digital shape, such as the description of what we called its past, its present and its future. For example, an instance of *AcquisitionSession* includes information about the scanner used to acquire a real object constituting important documentation about *ShapeData*'s past. Supposing that the type of the produced Shape Data is a *Mesh,* we can focus on some information intrinsically held by itself (and so related to its present)*, e.g.* the number of vertices or faces.

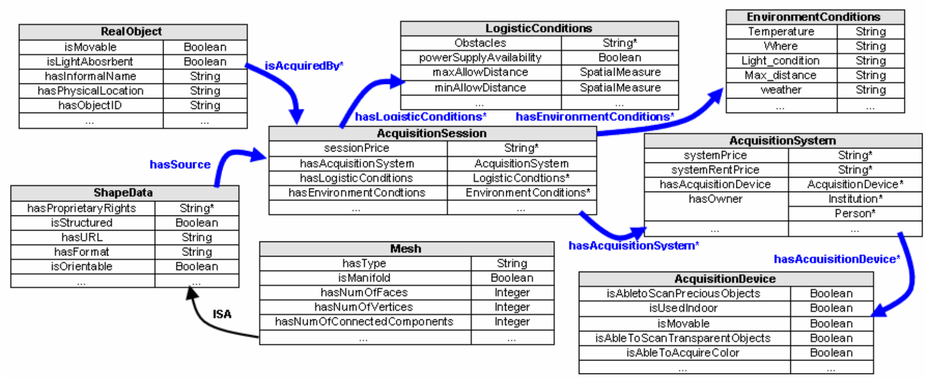

Fig. 3. A fragment focused on *AcquisitionSession* in our ontology for Shape Acquisition and Reconstruction. The most significant relationships are highlighted by arrows

At the same time, the number of vertices of a *Mesh* can be useful to plan future steps. For example, if we are interested in a surface mesh with at least 10.000 vertices and we found a surface mesh with 3.000 vertices, we could decide to plan a new *AcquisitionSession* increasing the accuracy of the *AcquisitionSystem*. In this case, the ontology supports the planning of a new *AcquisitionSession* providing information such as which *AcquisitionSystem*s are available (indicating also the owners of them), the prices to rent these systems, and so on. The concepts represented in the ontology, being selected according to the experts' skills, provide the right expressiveness to describe and to gather the resources.

5. The DSW Architecture to Support Search

The *Digital Shape Workbench* (DSW) is aimed at laying the basis for a common research platform for modelling, storing, processing and reasoning about shape models and software tools. At the core of the infrastructure, the ontology and metadata server constitutes the knowledge base that conceptualizes and provides persistency services for the knowledge in the field of shapes. Built on top of the ontology server, services for supporting inference and searching are provided.

The shape models and the software tools are organized in distributed repositories accessible via common APIs. A high-level view of the architecture is shown in **Fig.4**. The

Search and Inference Engine is probably the most important component of the DSW architecture and addresses the problem of searching for available resources in the knowledge base. The purpose of this engine is to provide non-trivial quality of service. In this case we are not simply interested in searching for resources; rather we are interested in searching intelligently.
We deal with this objective by specifying the ontologies (as the AR ontology presented in the previous section) in OWL, which provides some support for deductive reasoning, and by using a DL reasoner as Racer for providing the required inference capabilities.

The search engine provides a unified interface, to be used for accessing metadata information stored in the domain ontologies. Queries submitted using the search engine interface will place some semantic criteria on the metadata associated with digital shapes. The search engine will then use deductive reasoning and inference to find resources that match the specified criteria. One of the most important aspects of searching is to establish how to search. In our case, the way of searching is related to the user comprehension of the domain and of the structure of its conceptualization.

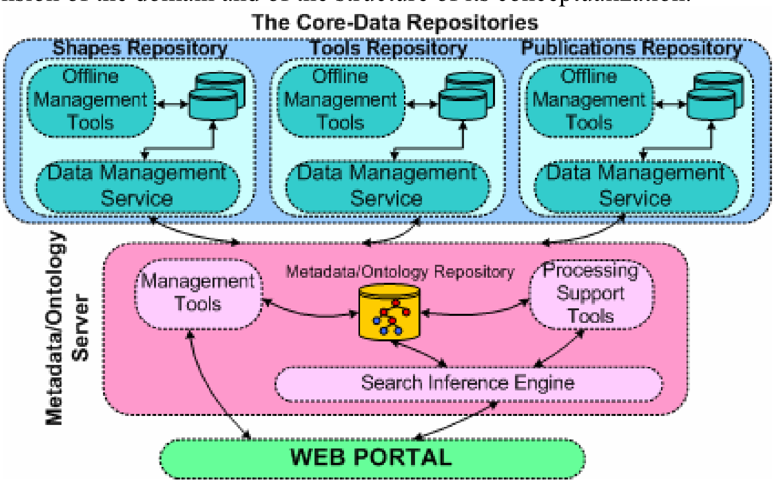

Fig. 4. The DSW Architecture. The core data repositories are interrelated with the Metadata/ontology server and queried from the web portal via the Search Inference Engine

Anyway, the AR ontology has been built taking into account the knowledge of the experts in the field of Shape Modelling. This ensures that it provides the right expressiveness to describe and to gather the resources (shapes, tools and publications).

To help the user in making efficient and appropriate queries, taking full advantage of the search and inference mechanisms, we are developing a graphical user interface that adds yet another level of abstraction. To simplify GUI development, a semantic layer is built on top of Racer that uses the DIG interface [27] for communication, thus ensuring independence of reasoner specific functionality. This layer provides basic class- and instance-level reasoning constituting a general-purpose framework for accessing inference engines that support the DIG language. The goal of the graphical interface is to provide the user with the means to search in an intuitive and straightforward way, without sacrificing flexibility and expressiveness of the queries. Furthermore, the user is able to store and reuse predefined or user-defined queries. Processing support tools provide additional functionality in answering queries that the ontology mechanisms alone cannot answer. This kind of queries does not involve only domain knowledge, which is captured by the ontology, but some processing as well. Examples of such queries are: transforming a shape from one representation to another, producing some similarity estimation between two shapes, and so on. Management tools are provided in the DSW in order to assist in the efficient management of the ontology and metadata repository. These include tools for creating, editing, parsing and validating, loading, browsing and visualizing ontologies and metadata descriptions. Furthermore, a unified web interface to these tools will be provided, in order to, along with the search engine, provide a single point of access to ontology management operations.

The DSW constitutes the first step in the development of a large-scale e-science framework promoting research on shapes, by formalizing, processing and sharing knowledge about digital shapes and their applications. The scalability of this approach will eventually lead to the actual exploitation of the Shape Modelling domain knowledge within the Semantic Web.

6. Concluding Remarks

The paper proposes an ontology-based searching framework for digital shapes. It aims to address the need of a new approach to store and retrieve shapes, tools and publications related to the field of Shape Modelling. This need is rapidly emerging from different social contexts and in particular from the scientific community. The proposed framework relies on the Digital Shape Workbench (DSW) and on a conceptualisation of the domains within the field of Shape Modelling. The DSW provides a common research platform for modelling, storing, processing and reasoning about digital resources, whereas the conceptualisation provides a characterization of the relevant resources and their related knowledge in order to retrieve them with a sufficient expressiveness. Due to the complexity of the field, it is not possible to represent the conceptualisation in terms of a monolithic ontology and therefore different ontologies have been designed. The aim is to address multiple contexts and applications where the shape knowledge can be exploited. In particular, the paper presents the DSW architecture and the ontology for Shape Acquisition and Reconstruction, as a portion of the whole conceptualisation, in order to demonstrate the capabilities of the entire framework.

The contribution of this work is twofold: on the one hand it contributes to the goal of the Semantic Web, adding essential semantics for content-based information and knowledge retrieval; on the other hand it boosts the scientific enterprise paving the way to a more efficient collaboration among scientists.

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