KNOWLEDGE-BASED REPRESENTATION OF 3D MEDIA

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Abstract. In recent years, 3D media have become more and more widespread and have been made available in numerous online repositories. A systematic and formal approach for representing and organizing shape-related information is needed to share 3D media, to communicate the knowledge associated to shape modelling processes and to facilitate its reuse in useful cross-domain usage scenarios. In this paper we present an initial attempt to formalize an ontology for digital shapes, called the Common Shape Ontology (CSO). We discuss about the rationale, the requirements and the scope of this ontology, we present in detail its structure and describe the most relevant choices related to its development. Finally, we show how the CSO conceptualization is used in domain-specific application scenarios.

Keywords: digital shapes, semantics, ontology, metadata, knowledge technologies**.**

1. Introduction

In the last decade, we witnessed an unprecedented improvement in technologies for multimedia delivery: internet bandwidth, compression methods, visualization capabilities now allow for streaming, sharing and rendering of multimedia content both in professional and personal environments. Semantic multimedia, as the evolution of traditional multimedia, make it possible to use and share content of multiple forms, endowed with some kind of intelligence, accessible in digital form and in distributed or networked environments.

In this panorama, 3D content is emerging as a new type of media and it is now widely recognized as the upcoming wave of digital media: the success of 3D communities and mapping applications (e.g., Second Life, GoogleEarth) and the decreasing costs of producing 3D environments are leading analysts to predict that a dramatic shift is taking place in the way people perceive and relate to 3D content.

The ease of producing and/or collecting data in digital form has caused a gradual change of paradigm in various applied and scientific fields, from physical prototypes and

experience to virtual prototypes and simulation. This change has an enormous impact on a number of industrial and scientific sectors, such as design and manufacturing, serious gaming and simulation, cultural heritage and archaeology, medical applications, bioinformatics and pharmaceutical science, where 3D media are essential knowledge carriers and represent a huge economic factor in many content sectors.

This rapid technological evolution motivates the growing need for knowledge-based systems for 3D media. These systems should be able to answer to the emerging needs of the variegated community of users facing the problems of sharing, structuring and accessing the information carried by 3D content.

Semantic 3D media, however, call for the development of *ad hoc* solutions for content- and context-based sharing, re-use and retrieval, for at least two reasons. First, the approaches developed for 2D media do not generalize directly to 3D. Research on multimedia and semantic multimedia is indeed largely devoted to pixel-based content which is at most two-dimensional (e.g. images), possibly with the addition of time and audio (e.g., animations or videos). 3D media, instead, are mainly characterized by vector-based representations, such as triangle meshes or parametric surfaces. On the one hand, they are much more complex in terms of properties characterizing the various representations, and require the definition of more elaborate knowledge conceptualizations to reflect properly the variety and the heterogeneity of 3D media representation types; on the other hand, they represent more realistically and reliably the world and the objects we are used to deal with.

Second, the context of use of traditional multimedia is mainly related to entertainment and personal interaction scenarios, while 3D media are produced, modeled, used, analyzed and exchanged in a variety of scenarios and users that range from the online gaming to highly-specialized engineering sectors.

In this paper we argue that, to support the next generation of media, 3D media should be stored with a comprehensive description of their content, from the geometrical information up to the knowledge pertaining to the context in which they are used. Preserving such knowledge and making it available through agreed formal schemes enhances the value of each object and strengthens its potential for reuse in diverse application areas. In this context, the AIM@SHAPE Network of Excellence [1] made a pioneering effort towards the promotion of a new semantics-oriented approach to model, retrieve, process and share knowledge related to multi-dimensional content in order to facilitate its re-use for producing new content. AIM@SHAPE addressed a wide domain of media by focusing on *digital shapes* as a generalized concept which encapsulates any multi-dimensional media characterized by a visual appearance in a space of 2, 3, or more dimensions [2], with a particular emphasis on 3D models and animations.

The general approach of the work done in AIM@SHAPE consisted in decoupling the formalization of knowledge related to the geometric representation of digital shapes from the formalization of knowledge about them in specific application domains. Even if the descriptions of an object can vary according to the various contexts, its geometry remains the same and can be captured by a set of metadata that, together with the core data, fully describe the properties of the geometric representation used. The knowledge related to the application domain in which shapes are manipulated is another key ingredient, as the

application context has a significant influence in the way the shape is processed and interpreted. Therefore, the formalization of the geometric knowledge ensures scalability in the process of building application-specific conceptualizations.
The focus of this paper is on the specification of a high level *ontology* for digital shapes – *the Common Shape Ontology* (CSO) – which has been developed within AIM@SHAPE, and whose role is to use a formalism to express the knowledge about digital shapes that is common to all application-specific scenarios considered. The CSO covers the most essential aspects of knowledge pertaining to the geometric representation of digital shapes, while the full spectrum of information carried or implied by digital shapes is expressed by domain-specific ontologies (also developed within AIM@SHAPE) for which the CSO works as a shared keystone. For example, there are cases where more emphasis should be put on capturing and representing information about the usage of a shape, which can be even more important than its geometric details. In a computer game, for example, the functionality of a simple chair can be more important than its appearance. Associating such kind of information to the digital model allows for answering many complex queries such as *deciding if a chair can be grasped by a character in the game*, or *whether a specific character is associated with animations that can be used with a stool in the game*.

The remainder of the paper is organized as follows. In Section 2, we introduce some background details about the various geometric representation types of 3D media and the concept of structural representation. In Section 3, we discuss related work concerning the semantic multimedia and recent work on the annotation of 3D media. We present an overview of the CSO structure in Section 4, while Section 5 contains usage scenarios of the CSO in various relevant contexts. We conclude with some remarks and future directions in Section 6. An Appendix is also provided where the reader may refer to, for definitions of certain technical terms.

2. Background

The digital representations of 3D objects provide information serving a number of application purposes. They may refer either to objects physically existing or to objects created and existing in a virtual environment. The massive impact of 3D content in everyday life can be already observed in application domains spanning from edu-entertainment to scientific visualization. Examples are provided by virtual games and consoles where 3D models are used and manipulated in order to create virtual worlds for simulating wars, battles, car competitions and so on. Another crucial application is medicine, such as surgical planning: in many cases, digital shapes of different dimensions (e.g. Magnetic Resonance Imaging, i.e. MRI, and 3D models) are mixed together to support the surgeon in understanding the conditions of the organ to be operated and in planning the surgical operation.
AIM@SHAPE suggested a high-level subdivision of the knowledge carried by digital representations of 3D objects into three levels of granularity with respect to their knowledge content: the *geometric*, *structural* and *semantic* levels.

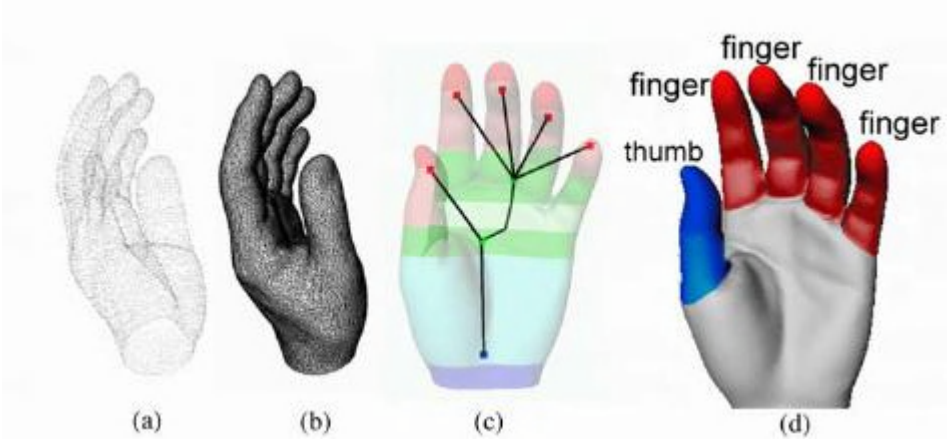

Fig. 1 - A digital shape represented by a point cloud (a); a geometric model of the point cloud, defined as a triangle mesh (b); the structure of the model, defined as a configuration of protrusion-like features (c); the model has been semantically annotated exploiting its underlying structure (d).

At the *geometric level*, a digital shape is represented by coding its form using a suitable geometric representation scheme, such as a triangle mesh, a Non Uniform Rational B-Splines (NURBS) surface or even more simply a set of points. In Section 4, the most common geometric representations are shortly introduced together with their conceptualization and in the Appendix a more detailed list of keywords can be found.

Generally, a purely geometrical representation defines and codes the spatial characterization of the shape and it is used to allow the user to interact with it by visualizing the shape, and to support a number of analysis processes, such as intersecting shapes or computing automatically any interesting quantity related to them [3] (see **Fig. 1**a). Geometric information also supports the simulation of physical properties of a given material, such as the elasticity of human tissues [4].

A *structural view* of a digital shape gives an abstraction, identifying the portions or segments that are relevant and how they are connected together. The process of structuring a digital shape requires the geometric or morphological analysis of the geometrical representation, and it is often related to the extraction of relevant form features. This analysis induces a structural description of the object for instance by means of a segmentation or a skeletonization process (see **Fig. 1**c). Examples are given by adjacency graphs obtained by segmenting an object in tubular parts, and skeletons based on the Medial Axis Transform, respectively [5][6].

It can be noted that different structural representations can be used to describe the same shape in various manners, depending on the characteristics that one wants to highlight in the object. From a cognitive point of view, structural representations are richer than geometric ones, meaning that they capture and explicitly code parts of the shape by clustering the atomic surface elements into bigger and more meaningful chunks.

In our vision, structural models can be seen as a bridge between geometry and semantics, as they resemble and mimic the human perception of objects as structures of parts.

Finally, a *semantic view* of a digital shape makes its interpretation explicit in a given knowledge domain, for example, by associating an object to a specific class or by associating a semantic label to specific portions of the shape (see **Fig. 1**d). Obviously, the perception of a shape strongly depends on the specific application domain. In fact, some portions of the shape can be "meaningful" in some domains and completely useless in others. The association of semantic labels to parts of the shape makes machine-tractable the knowledge and meaning about the object. For example, let us imagine that we have to design the interaction of an avatar with a teapot in a virtual environment. A semantic model of the teapot, which stores explicitly the tag that localizes the handle, would be more easily processed by an automatic grasping analysis performed by the avatar to "understand" where the object could be grasped.

It has to be noted also that, beside intrinsic shape properties, other important object characteristics exist, which are totally independent of their shape, e.g., the ownership, the history about the acquisition, the material of an object can be very useful in some application domains.

Fig. 2 presents an example of a 3D digital shape and its relevant characteristics: it can be seen as simple resource (e.g. name and URL), or it can be considered by its geometric characteristics (e.g. a set of triangles and normals). The shape has a structure (e.g. the skeleton of a teapot) or it can be seen as composed by a handle, a spout, a body and a tip.

Due to the intrinsic complexity of shapes, we believe that ontology-driven metadata are necessary in order to reach a higher level of expressiveness. Metadata provide a thorough characterization of shapes by storing also the information intrinsically held by the shape itself. Moreover, ontology-driven metadata are able to represent the different levels described above, i.e. 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).

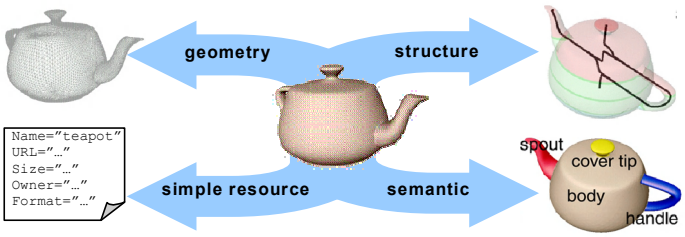

Fig. 2 - A shape is described as a simple resource, or by its geometry, its structure, its semantics, depending on the application domain.

3. Related work

Semantic description of multimedia items has been mainly developed for audio, video and still images. Domain-specific ontologies are focused on describing the content and the parts of a multimedia scenario, such as elements in a scene, colors, motion duration, etc. These descriptions are defined in order to be able to categorize, retrieve and reuse

multimedia elements as described in [7]. Examples of domain-specific ontologies and metadata have been developed for a wide set of applications, from Cultural Heritage [18] to Biomedicine [8].

Most of these kinds of ontologies which deal with content description make complete or partial use of the MPEG-7 standard [9]. The MPEG-7 standard, formally named *Multimedia Content Description Interface*, provides a rich set of standardized tools to describe multimedia content (still pictures, graphics, 3D models, audio, speech, video, and composition information) regarding how these elements are combined in a multimedia presentation independent of storage, coding, display, transmission, medium, or technology. Furthermore, MPEG-7 also provides an ontology [10] which embodies a general and large representation of metadata. The Visual Descriptors Ontology [11], written in RDFS [12], aims to offer a more extensive description of the visual part of MPEG-7; this is primarily addressed by supporting automatic content annotation using reasoning and providing access to specific domains.

Less common descriptions are used for those elements that are not necessarily audiovisuals, such as the format, the methodology used in the creation, and the inclusion of personal content. The Core Ontology for Multimedia (COMM) [13] is another ontology that extends MPEG-7 to provide richer multimedia semantics by using generic software patterns which create a layer between MPEG-7 concepts and domain-specific interpretations.

There are efforts towards a generalized multimedia ontology [24], which represent the challenge of unifying concepts among domain specific and top-level ontologies. However, top-level ontologies are still too general to cover the description of multimedia elements targeted in this paper, and the domain specific ontologies do not consider all kinds of elements that we can find in multimedia, in particular 3D shapes. OntologyX3D [14] is a dedicated 3D ontology mapped from the X3D standard. It represents graphic elements and virtual reality concepts, which makes it domain-specific.

The limited consideration of 3D shapes is due, to a large extent, by the partial level of accessibility to this kind of multimedia, which is still immature. Nevertheless, due to the advances in 3D modeling and knowledge management technologies related to creating and reusing this kind of content, 3D shapes are getting closer to becoming part of common multimedia like images and videos.

In 2006 the Khronos Group started to work on an advanced 3D asset description: COLLADA. This is referred to as the industry's first standard interchange format for digital content. It is an XML-based file format supporting the transfer of common types of 3D data between applications. It is also an extensible format that is foreseen to grow to support increasingly sophisticated 3D features, as they evolve [15].

The Common Shape Ontology presented in this paper targets different kinds of multimedia content, ranging from 2D/3D images to videos, 3D models and 3D animations, and maintains top-level information that is sharable and usable in different domains. Nevertheless, unlike most of the aforementioned ontologies, the CSO deals with 3D models as a key resource type, focusing on their specificities: it has been designed and used for a full characterization of shapes in the AIM@SHAPE Shape Repository [25]. The information carried by the CSO ontology can be also used to enrich

the data representation in COLLADA, exploiting its extensible nature: in order to maximize sharing and reuse of resources in different context, a virtuous combination of different frameworks for describing and characterizing 3D is an added value in the scientific community.

4. The Common Ontology for Digital Shapes

An ontology is designed to define unambiguously the meaning of terms in a specific context by breaking them down into formal concepts with explicit relationships. Although still an evolving discipline, ontology engineering has widely and rapidly been adopted by computer science communities for different application contexts.

Ontologies are a key enabling technology for the Semantic Web as they interweave human understanding of symbols with their machine processability. The use of ontologies and supporting tools offers an opportunity to improve significantly knowledge management capabilities.

In the case at hand, an ontology-driven representation is used to provide an expressive characterization of shapes at different levels of abstraction and to ensure that existing tools, such as Description Logic reasoners [16], can be used to reason on shape repositories and deduce explicitly information that would be either implicit or missing in other representation schemes.

The Common Shape Ontology conceptualizes knowledge that addresses several domains within the discipline of Shape Modeling. The motivation for creating the ontology is the ability to reason, to re-use existing knowledge and to create new knowledge about shape resources. The CSO focuses on the geometric and structural representation of digital shapes delegating semantic modeling to context-dependent conceptualizations. It can be used to describe some general metadata about shape objects, and could also constitute the foundation for domain-specific ontologies. In fact, it is referred to as common because there are three domain ontologies developed in AIM@SHAPE, namely the Product Design Ontology (PDO) [19], the Virtual Human Ontology (VH) [23] and the Shape Acquisition and Processing Ontology (SAP) [22] which extend CSO. The motivation and objectives for each of the domain ontologies is shortly presented in the following section.

In order to design these four ontologies we adopted the methodology introduced in the On-To-Knowledge project [20], which is characterized by the early specification of the requirements through the formalisation of competency questions (i.e. questions that should be answered using only the information included in the ontology) and an iteration of a refinement phase, an evaluation phase and a maintenance phase.

An overview of the Common Shape Ontology structure, where the most important concepts are shown, is given in **Fig. 3**. As can be seen, the basic structure of the CSO ontology is simple enough to promote reusability. In order to understand the rationale behind the choices made for the conceptualization, it is important to keep in mind that the intended target of the ontology are the scientific researchers, and that the information is not only related to the shapes themselves, but also to their role inside the AIM@SHAPE Shape Repository [25].

Furthermore, the structure of the CSO reflects how a domain application would use it to record and refer to geometric information relevant to its specific context. More specifically, a domain application will use the CSO to handle geometric or structural characterization of the shapes as well as information about their storage, grouping, provenance and ownership.
This will become clearer after the description that follows, which identifies the most important aspects to potential application scenarios, and its usage in practice will become more evident in the scenarios of section 5.

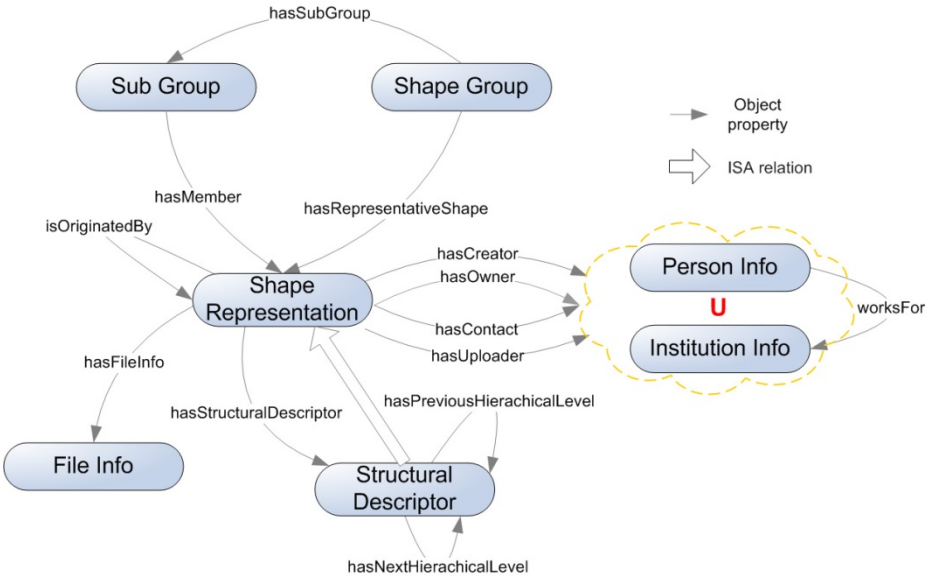

Fig. 3. - An overview of the structure of the Common Shape Ontology.

The most important concepts in the ontology are the *Shape Representation* class and its specializations, whose instances are the actual digital shapes. First of all, a digital shape can be regarded as a generic resource; thus, a *Shape Representation* is an abstract concept encapsulating information that is inherent to the shape model itself. The users are typically interested in getting information about the contact person or institution associated with a shape, and therefore specific relations address the creator, the owner, the contact and the uploader of a digital shape. Since the granularity of these roles is not often well defined, the range of the above relations is *Person Info* and *Institution Info*, which in turn can be mutually linked by the relation *worksFor*. Another simple yet important way to look at a digital shape is to consider it as a file. For this reason each shape can be related to a *File Info* instance, in which the information about the name, the size, the format and the URL of the file are stored.
Another way in which digital shapes can be considered is related to the ability of clustering them in groups. This feature is mostly related to the way they are stored in the repository, yet it reflects some common attitude of researchers toward shapes. In our conceptualization different shapes can be clustered in a single group, and each group may

be characterized by a representative shape (mainly for visualisation purposes, the shape which stands for the whole group). Furthermore, subdivisions in subgroups may take place, which reflect a possible hierarchy or generation order between the models. There are different reasons for the need of creating the *Group* concept. For instance, possible reasons for grouping different shapes are:

(i) they are all parts of a more complex CAD model (in this case the representative shape could be the entire CAD model);
(ii) they constitute the benchmark eligible for running tests on specific algorithms;
(iii) they represent variations, products or by-products of the processing stages of an original shape;
(iv) they are the results of different scans in an acquisition phase, which will possibly be registered, combined, and merged in a unique 3D shape. In this last case it is likely that the representative shape of the group would be the final shape.

The core of the CSO is the conceptualisation of the *Shape Representation* concept. It should be noted that the goal is not only to provide a useful categorization of the digital shapes, but also to provide each category with its own specific attributes and relations. An overview of the hierarchy rooted in the *Shape Representation* class is shown in **Fig. 4**. The different class levels are drawn in different colour in the diagram. First level classes are shown in light blue colour, second level classes are shown in yellow colour and third level classes are shown in orange colour in the hierarchy. Please, refer to the Appendix to make all the definitions we used for the concepts of this taxonomy clear. We have omitted the relations (object properties) and the attributes (datatype properties) for the various classes in the diagram.

An overview of the first level follows. Firstly, the *Geometrical Representation* class includes shape descriptions based on geometry, while the *B-Rep* class gives more emphasis to the topological information of the shape. The two classes are not disjoint, since formally a mesh is a B-Rep (boundary representation) and the choice of classifying a shape as belonging to one class or to the other depends mainly on the application context. In fact, the Computer Graphics community commonly adopts a mesh description for shapes and the terminology is definitely standard today, while other fields such as CAD traditionally prefer to use the more general B-Rep description. The boundary representation defines objects in terms of faces, edges and vertices which make up their boundary. The properties identified in the CSO favor the topological aspect, considering for example the continuity degree between the faces and its topological complexity.

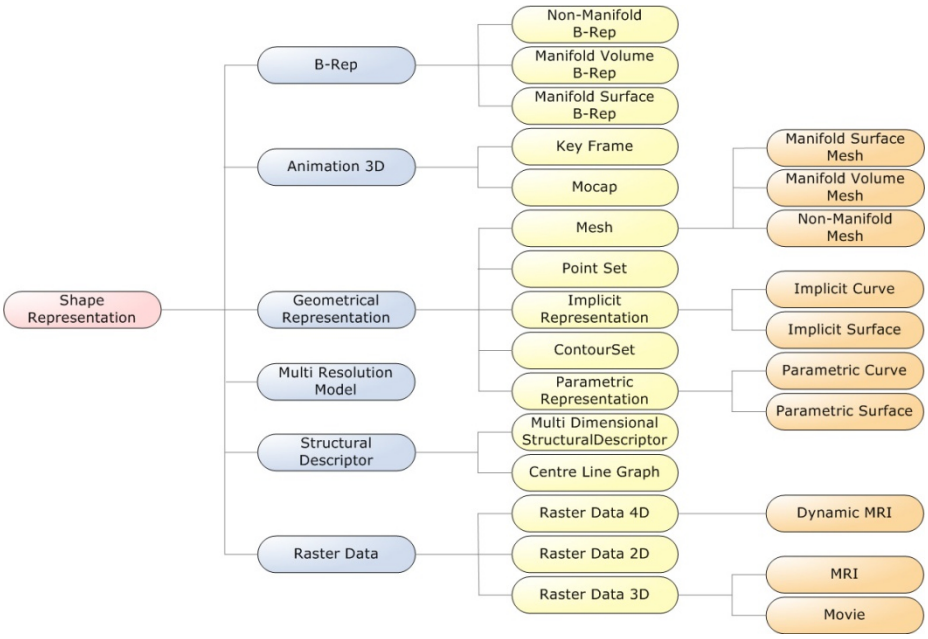

Fig. 4. - An overview of the hierarchy rooted in the *Shape Representation* class.

The attributes defined for the different subclasses of *Geometrical Representation* focus on geometrical aspects. The *Multi Resolution Model* class formalizes models represented in a way which allows for a manipulation of geometry at different resolutions, enabling both local and global modification, and modulation of details at different frequencies. The main properties here are related to the granularity of the model, to the minimum and maximum resolution of the models contained and to the method used to simplify recursively the original shape. The *Animation 3D* class collects information related to the animation of a shape and can have relationships with the geometrical and structural representation of the shape. The *Structural Descriptor* class models the structural views of 3D shapes and refers to decompositions of a shape into its relevant parts, together with the adjacency relationships among them. Structural descriptors can be used for an efficient classification, recognition, comparison, and retrieval because they provide a meaningful abstraction of a shape. One property of this class refers to the creation method of the specific instance and, in case a center-line graph is obtained, the information related to the number of arcs and nodes as well as other typical properties of graphs are included as properties. Finally, the *Raster Data* class formalizes the information stored in a grid of cells; raster data are commonly used to represent images (2D raster grids), videos and MRI volumes (3D raster grids). The properties related to this class include information about the grid and the single cells, such as dimension, intensity values and RGB values.

More specialized classes and their corresponding attributes have been modeled in the subclasses, which are not reported here. For a complete overview of the ontology and the meaning of the different concepts, the Digital Shape Workbench (DSW) [26] can be browsed, which also includes a glossary with short descriptions for relevant concepts and terms.

5. The Common Shape Ontology: Usage Scenarios

To demonstrate that the Common Shape Ontology (CSO) can be successfully used in domain-specific ontologies, in this section we present two specific user scenarios. The first one is related to the acquisition of a human shape and the production of an animated virtual human while the second one concerns the product development process.

5.1. *Domain-specific ontologies overview*

The user scenarios we are going to present next involve concepts defined in the Common Shape Ontology (Section 4) as well as concepts and relations from three specific domain ontologies developed within AIM@SHAPE. These ontologies are the Shape Acquisition and Processing Ontology (SAP), the Virtual Human Ontology (VH) and the Product Design Ontology (PDO). The formal specifications of these ontologies are freely available from the AIM@SHAPE project website (described in OWL format [27]) along with online tutorials for a better understanding of their scope and usage [26].

In particular, the **Shape Acquisition and Processing Ontology** (**SAP**) conceptualizes the domain 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 processing of shapes*. The fundamental goal of the ontology is to formalize the knowledge related to the Acquisition and Processing of a shape [22].

The **Virtual Human Ontology** (**VH**) is related to the *description of complex 3D entities such as virtual humans, not only at the geometric level, but also at the structural and semantic level.* The goal of this description is to simplify the composition of virtual humans by non-experts and to facilitate sharing of useful information by domain experts in order to promote reusability and scalability[22].

Finally, the **Product Design Ontology** (**PDO**) addresses researchers in industrial product design and engineering analysis who need to share shape data and to develop software tools. The focus of this formalization is on the task-specific information associated to a shape, and the functionality and usage of shape processing methods in specific tasks of the design workflow [19].

The above three ontologies have been designed based on the expertise of the researchers involved and can be particularly useful within the Shape Modeling community. In the following subsections we describe in detail two usage scenarios, outlining how the Common Shape Ontology and the domain-specific ontologies are being used. One important requirement of these case studies is the understanding of the underlying semantic structure and the organization of the domain specific ontology. This can significantly improve the query formulation process.

5.2. *Acquisition of a Human Body*

The first scenario on which we focus is related to a human body acquisition for creating an animated virtual human starting from a real person. A scenario like this is crucial for those applications aiming at making virtual simulations involving humans, such as the population of Virtual Environments, where one of the main challenges is to create a large

diversity of human characters to fulfill the demand of a large amount of users. This example requires the organization and maintenance of information at different levels from the geometrical aspects up to the description of abstract concepts such as the personality and emotional traits to individualize Virtual Humans.

The scenario is based on two domain-specific ontologies: the Shape Acquisition and Processing (SAP) and the Virtual Human (VH) and it uses also concepts from the CSO ontology, extending the SAP and VH ontologies the CSO. In the description of the scenario, we will refer to concepts and instances belonging to the three ontologies using prefixes. In particular:

- "*CSO:*" when a concept belongs to the Common Shape Ontology*;*
- *"SAP:*" when concept belongs to the Shape Acquisition and Processing Ontology;
- "*VH:*" when the concept is modeled in the Virtual Human ontology.

Note that, the Acquisition and Processing and the Virtual Human Ontologies formalize concepts that are relevant for them without neglecting information in CSO, which is also relevant for domain applications. In **Fig. 5** the different concepts and relations involving the human shape acquisition are depicted. The scenario is presented as a workflow of actions (scanning, reconstruction, analysis and synthesis) for obtaining an animated virtual human (instance of *VH:VirtualHuman*) from a real object (the human person – instance of the concept *SAP:RealPerson*). Every action is foreseen in the conceptualization of the corresponding domain ontology.

Focusing on each specific action, the process starts with the scanning session (instance of *SAP:AcquisitionSession*), where we acquire a points cloud (instance of *CSO:PointSet*), which is a set of points in a 3D space, from the real person. This acquisition can be performed with a dedicated scanner, a set of cameras or any other suitable acquisition system (instance of *SAP:AcquisitionSystem*). The acquisition session modeled in the SAP formalizes all the necessary knowledge related to the acquisition phase, including the logistic and environmental conditions under which the scanning has been performed. Furthermore, detailed information about the acquisition system is maintained. Following the acquisition session, and starting from the points cloud produced, a surface reconstruction session is started (instance of *SAP:ToolSession*). The reconstruction is carried out with specific software tools (instances of *SAP:SoftwareTool*), which performs meshing, merging and hole filling operations. Finally, a non-manifold surface mesh (instance of *CSO:NonManifoldMesh*) is created. At this step, we already have a geometrical digital representation of the real person. However, we still need to analyze the shape in order to create the attributes that will allow us to generate the virtual representation of the real person. This means that we need to add an internal structure so that the mesh may be deformed and an animation may be applied. This step requires making an analysis of the shape for its segmentation, annotation and mapping. A phase of analysis and mapping is therefore started (again, an instance of *SAP:ToolSession*) which uses a specific tool (e.g. *Plumber*, instance of *SAP:SoftwareTool*). From this step, we obtain as output a structural representation of the shape (*EllaBody*, an instance of *CSO:MultiDimensional StructuralDescriptor*) which can be represented, for example, in an h-Anim format as defined in [21]. In the phase of synthesis, the intervention of an expert is necessary, in this case a designer, who can create a 3D character from the

previous annotated shape and add the needed features such as an skeleton and textures to be able to use the virtual human inside a 3D environment.
We can further describe this final shape object with respect to another specific domain, which is captured by the VH ontology. The Virtual Human concept is a human shape that has a geometry and a skeletal structure (*VirtualHumanElla* becomes an instance of *VH:VirtualHuman* because it has Geometry and Skeleton in its *EllaBody*). This final geometry with skeletal structure allows to populate a 3D environment with this character and to apply animations on her.

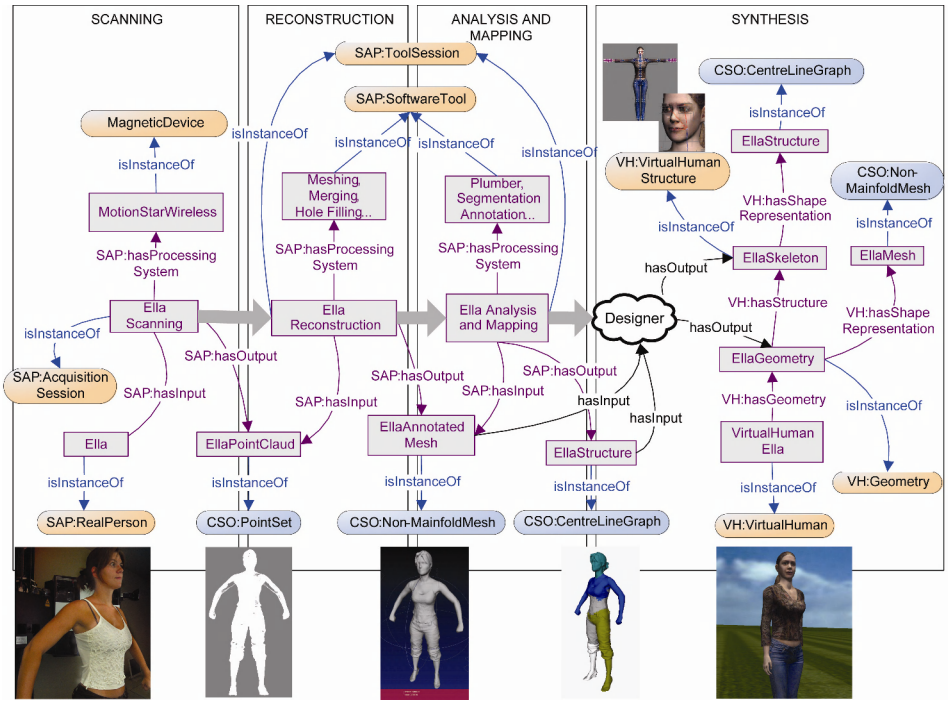

Fig. 5. - Description of the acquisition and processing phases of a Human Shape. Different sessions are described as instances of the SAP ontology, while shapes resulting from those sessions are instances of the CSO. And, instances referring to the final synthesized Virtual Human correspond to the VH ontology.

During this creation pipeline the history of the shape is stored in the CSO. This allows us to answer competency questions such as: *What shape originated from shape 'EllaMesh'?, What kind of structure conforms the skeleton of this Virtual Human? Which shapes were generated from the shape "EllaPointClaud"? Who is the owner the shape 'Frog'?*. Furthermore, the SAP and VH also serves in answering domain specific questions, e.g: *Which software was used to annotate the shape "EllaAnnotatedMesh"? Which is the real person used to create the animated virtual human 'Michela'?*, *Under which lighting conditions did the real person create this virtual human*?, *What animations can be used by this virtual human?*

5.3. *Digital Product Workflow in Simulation*

The second scenario is related with the product design process. Product design is the first phase of the overall product development process, which deals with all the aspects concerning the realization of an artifact. Due to worldwide competition and technological improvements in the last years, product time-to-market has been reduced and specialization in the Product Development Process (PDP) has been growing. PDP is a very complex process which requires different expertise, according to the specific activity considered. Due to such change of mentality in the design activity, companies and actors of the PDP need to have access to the right information at the right time in a usable format in order to perform an efficient job. It follows that PDP requires not only a large number of information and data, suitable for any specific application, but also a strong interaction among the actors to share and retrieve product data.

The Product Design Ontology (PDO) focuses on the annotation and retrieval of shape information in two specific tasks of the PDP, namely the *free-form modeling* and the *engineering analysis*. Therefore, it is strictly interconnected with the CSO since the goal in this ontology is to assist researchers who need information related to the shapes and tools intervening in the two mentioned tasks.

In the PDO two main aspects of a shape are considered within the design process:

- The *role of a shape* during the product development process to interpret the task-specific information;
- The *functionality and usage* of shape processing methods and algorithms in order to model and evaluate a shape according to the task-specific needs.

Here we present a typical usage scenario of the PDO related to the engineering analysis, also mentioned as *simulation phase*. It evaluates the physical behavior of any engineering component of a product, which is subject to various kinds of loads and conditions, ranging from structural analysis to thermal and electrical analysis, and so on. As in the case of the previous scenario, we use prefixes in the concepts and instances in order to describe their belonging to one of the two ontologies involved. In particular:

- *"CSO:*" when a concept belongs to the Common Shape Ontology*;*
- "*PDO*:" when the concept belongs to the Product Design Ontology.

Error! Reference source not found. presents the workflow followed to perform a simulation on a mechanical part, which corresponds to the task *PDO:CalculationAndAnalysis,* which is a subclass of. *PDO:Task*, and follows the design task. The CAD model used to design the product is usually represented by parametric surfaces, which are suitable for manufacturing purposes, but not for performing a Finite Element Analysis (FEA). Therefore, the initial design model generated by a CAD system (in the picture the initial model is an instance of *CSO:ManifoldBRep*) needs to be converted into a FE mesh, the model required to run a simulation. In the PDO the input of the simulation is a digital shape, instance of *PDO:SimulationModel*. Consistently, the *role* (*PDO:ShapeRole*) of a simulation model is *PDO:FiniteElementMesh*, in particular, *PDO:PreSimulationMesh*, and has a shape representation that is an instance of *CSO:Mesh*.

More precisely, a FE mesh is a mesh which satisfies typical geometric conditions. Then, the subtask *PDO:GeometricDesignEvaluation* is dedicated to the verification of the

geometrical model. In fact, through a specific attribute of *PDO:ShapeRole* for *PDO:PreSimulatioMesh*, the necessary geometric properties for the specific simulation are listed, while through the metadata associated to the *CSO:Mesh*, it is possible to check if the mesh representing the engineering component has the required properties. If it does not, dedicated software tools included in the DSW can be acquired and utilized for correcting the mesh.

To reduce the complexity of the simulation it often happens that the design model is simplified, removing shape details which do not influence the results of the engineering analysis. Such operation can be applied both on the design model (as in Fig. 6 where the small holes disappeared) and on the FE mesh after the conversion. If a simplification is required, the role of the design model (or FE mesh) becomes *PDO:SimplificationModel* and a simplification task (*PDO:ShapeSimplification*) appears in the PDO: it mainly consists of a suitable editing and rearrangement of the geometric elements in the shape and therefore all the properties required to perform the simplification correctly and the associated queries refer directly to the CSO scheme.

Once the suitable model for simulation has been set, specific boundary conditions have to be imposed. They are physical conditions which describe the interactions of the component at the boundaries of the simulation region. In the PDO such activity corresponds to the task *PDO:DefinitionOfBoundaryConditions* and a taxonomy of Boundary Conditions, that is *PDO:Boundary ConditionType,* has been included, which subdivide them according to the specific simulation type (e.g., structural mechanical, electromagnetic, thermal analysis).

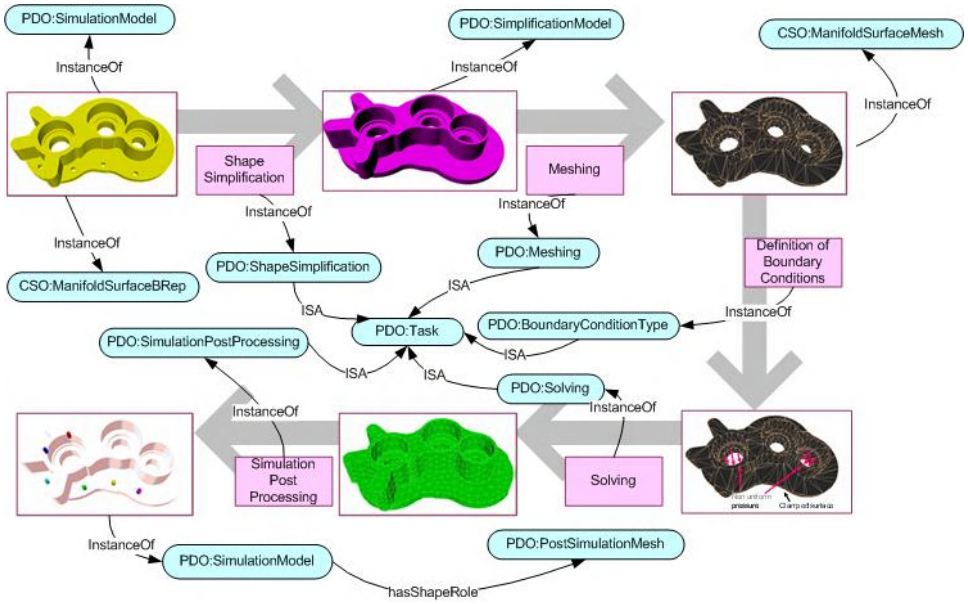

Fig. 6. - A typical digital simulation workflow: different tasks are applied to a design model of a mechanical component to perform an engineering analysis and produce a post-simulation model. In the diagram the reference to concepts of the PDO and the CSO are explicit. All the pink boxes are indirect instances of the PDO:Task; all the framed digital models are instances of concepts used in both the PDO and the CSO.

Now the simulation can be executed in the task *PDO:Solving* and the output shape is an instance of the *PDO:SimulationMesh* with the *role* of a *PDO:PostSimulationMesh*. Belonging to such class implies that the simulation results are associated to the geometric part. In the task *PDO:SimulationPostProcessing* the simulation outcome is interpreted considering also the influence of the shape details removed in the first phases of the process (in Fig. 6 the small holes have been included again), and finally decisions are made about the suitability of the design with respect to its engineering specification,.
This conceptualization allows us to answer to a large set of competency questions such as: *What type of conditions should the model 'Carter' have to fulfill before performing the Solving task?, Which kind of geometric checks do we have to consider when performing the ShapeSimplification task?, Which software tools are helpful to detect possible self-intersections on the model 'Carter'? What are the PDModels whose Shape Role is PostSimulationMesh?*.

6. Concluding Remarks and Future Directions

In this paper we have outlined our work towards capturing and representing formally knowledge related to digital shape content. We have presented the goals and the structure of the Common Shape Ontology, defined within the AIM@SHAPE Network of Excellence for structuring shape-related metadata. This Common Shape Ontology captures a shared conceptual schema common in the domain ontologies developed within the project, which actually represents the geometric part of digital shapes and in this sense applies to any digital shape.
This work has been also used to build a shape repository which follows the structure of the Common Shape Ontology and maintains semantic information for shape models, where each object represents an instance of a particular class in the specified ontology. The same approach could be adopted by other online digital shape repositories in order to enhance semantically their content. Moreover, a searching framework [17] has been developed for interacting with ontology-driven knowledge bases of multi-dimensional objects.
However, specifying the framework for annotating semantically digital shapes is only a step towards a larger vision. To fulfill this vision means to face and deal successfully with several remaining challenges:

- *(i)* Facilitate, where this is possible, automatic semantic annotation of digital shapes;
- *(ii)* Enhance repositories so as to exploit and reuse fully semantic annotations;
- *(iii)* Build semantic search engines to improve discovery and access to digital shapes;
- *(iv)* Build tools that are able to use this kind of semantic information to improve their potential for interaction with repositories and humans.

Each of these challenges constitutes a future path we need to traverse in order to facilitate the infrastructure and the tools which are necessary to take advantage of the semantic information that is associated with digital shapes. Within AIM@SHAPE we have worked towards this goal. For some specific types of digital shapes (namely, manifold surface meshes, non-manifold meshes, multi-dimensional structural descriptors and key frames), different automatic annotation tools have been developed [29] in order to extract useful

information from a specific digital shape and to maintain this information according to the metadata defined in the CSO. One step further has been achieved in the Network [30] with the development of a prototype system for the semi-automatic annotation of shapes and shape parts in a context specified by an ontology.
Future directions of the work presented here will be mainly focused in the four key areas that have been identified and will allow us to demonstrate the potential of utilizing not only the geometrical properties of multi-dimensional shapes, but their semantic-driven descriptions as well. This will be crucial in realizing the vision of developing intelligent agents and programs able to interoperate and access knowledge bases, dealing with multi-dimensional objects in the same way as with any other type of information in the Semantic Web today.

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9. Appendix

This appendix contains the relevant technical definitions used in the text above. A complete list of defined concepts during this work can be found in [21].

Animation sequence: Pre-recorded animation sequences (key-frame animation, etc.). In general, it contains the joint angle values and/or vertex displacements corresponding to the key animation frames. Different interpolation and codification methods can be used. Such sequences can be applied to one or many VH depending on the codification and technique being used.

Boundary representation (BRep): Geometric representation of objects defined in terms of the faces, edges and vertices which make up its boundary. The boundary of a three dimensional solid is a two dimensional surface, which is usually represented as a collection of faces. The segmentation of the surface into faces is usually performed so that the shape of each face has a compact mathematical representation, e.g. that the face lies on a single geometric surface. Faces, again, are often represented in terms of their boundary being a one-dimensional curve. Hence, boundary models may be viewed as a hierarchy of models.

Center line: The concept is strictly related to that of skeleton. Complex objects can be seen as the arrangement of tubular-like components, abstracted to a collection of center-lines which split and join, following the object topology, and which form a skeleton. A center-line should satisfy the following requirements: centricity, connectivity and singularity.

Contour: One or a set of curves originated through intersection of a plane with the object.

Contour set: Intersection curves between the surface and a family of parallel planes.

Dynamic Magnetic Resonance Imaging (DMRI): A sequence of MRI images to capture the motion of an object.

Implicit curve/surface: The set of points P in space verifying an implicit equation (f(P) - constant = 0). f is called the "field function" (and sometimes the "implicit function", which is improper since this function is explicitly given by its parametric equation).

Key-frame animation: Type of animation that is defined by a set of frames, where each frame contains a set of key frames which indicate the position and orientation of defined objects in the animation. Each key frame includes a key time which orders the set of key frames.

Manifold: A (separable Hausdoff) k-dimensional topological space M in which each point has a neighborhood which is homeomorphic either to the k-dimensional open ball or to the half-ball.

Mesh: A grid-like polygonal subdivision of the surface of a geometric model. It is a collection of vertices, edges and faces that defines the shape of a 3D polyhedral object.

Motion capture: Methods for capturing movement data from a live source. The data are filtered and processed in order to replicate the same motion as the one performed by the live source on a control skeleton.

Movie: Sequence of two dimensional images of a defined duration that produces an animated film, which can have audio. The dimensions are the two corresponding to the image and one to the time (x,y,t).

Magnetic Resonance Imaging (MRI): Three-dimensional images produced by a non-invasive diagnostic procedure that uses magnetic field resonance. MRI is commonly used to obtain 3D pictures of internal body structures. In the case of dynamic MRI it is the acquisition of a sequence of MRI images to monitor temporal changes in tissue structure.

Multi Resolution: An analysis and/or synthesis technique that allows for manipulation of geometry at different resolutions, enabling both local and global modification, modulation of details at different frequencies.

Multidimensional structural descriptor: A Multidimensional structural descriptor is based on atomic elements whose dimension is higher than one. For example, it may include also surfaces, and volumes.

Parametric curve/surface: Any curve/surface defined on a parametric domain. In case of surfaces, such domain can be usually tensor-based or triangular. Bezier, B-Splines, NURBS curves/surfaces belong to this category.

Point cloud (or point set): A set of uncorrelated points, usually in 3D, which have to be further elaborated to obtain a 3D model.

Raster data: One method of storing, representing or displaying spatial data in digital form. It consists of using cell data arranged in a regular grid pattern in which each unit (pixel or cell) within the grid is assigned an identifying value based on its characteristics.

Regular mesh: It is composed of simplices that are all similar (or belong to just few classes of congruent simplices) and have all vertices of the same degree (i.e. with the same number of incident simplices).

Shape representation: This abstract concept encapsulates information that is inherent to the shape model itself.

Structural descriptor: Description of a shape through the detection of its relevant parts, together with the adjacency relationships among them.

Virtual human: Specialized instance of an articulated character. The model can be synthesized in a variety of ways and can represent a real or a virtual person. VHs are characterized by a set of general attributes (sex, nationality, race ...), and structural descriptors (e.g., skeleton, geometry, landmarks).