THE SEMANTIC WEB3D: TOWARDS COMPREHENSIVE REPRESENTATION OF 3D CONTENT ON THE SEMANTIC WEB

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ABSTRACT

One of the main obstacles for wide dissemination of immersive virtual and augmented reality environments on the Web is the lack of integration between 3D technologies and web technologies, which are increasingly focused on collaboration, annotation and semantics. This gap can be filled by combining VR and AR with the Semantic Web, which is a significant trend in the development of the Web. The use of the Semantic Web may improve creation, representation, indexing, searching and processing of 3D web content by linking the content with formal and expressive descriptions of its meaning. Although several semantic approaches have been developed for 3D content, they are not explicitly linked to the available well-established 3D technologies, cover a limited set of 3D components and properties, and do not combine domain-specific and 3D-specific semantics. In this paper, we present the main motivations, concepts and development of the Semantic Web3D approach. It enables semantic ontology-based representation of 3D content built upon the Extensible 3D (X3D) standard. The approach can integrate the Semantic Web with interactive 3D technologies within different domains, thereby serving as a step towards building the next generation of the Web that incorporates semantic 3D contents.

Index Terms— virtual reality, Web3D, X3D, Semantic Web, ontologies, knowledge bases

1. INTRODUCTION

Immersive virtual reality (VR) and augmented reality (AR) environments are becoming more and more popular in various application domains due to the increasing network bandwidth as well as the availability of affordable advanced presentation and interaction devices, such as headsets and motion tracking systems. One of the most powerful and promising platforms for immersive VR/AR environments is the Web. It offers suitable conditions for collaborative development and use of VR/AR environments, including indexing, searching and processing of interactive 3D content of the environments. Development of web-based VR and AR has been enabled by various 3D formats (e.g., VRML [40] and X3D [41]), programming libraries (e.g., WebGL [3] and WebXR [38]) and game engines (e.g., Unreal [4] and Unity [32]).

These opportunities have been further enhanced with the advent of the Semantic Web [8], which is currently a prominent trend in the evolution of the Web. It transforms the Web into a network that links structured content with formal and expressive semantic descriptions. Semantic descriptions are enabled by structured data representation standards (in particular, the Resource Description Framework, RDF [36]), and by ontologies, which are *explicit specifications of a conceptualization* [19], i.e. knowledge organization systems that provide a formal conceptualization of the intended semantics of a knowledge domain or common sense human knowledge. Ontologies consist of statements that describe *terminology* (conceptualization)—particular classes and properties of objects. Ontologies are intended to be understandable to humans and processable by computers [8, 19]. In the 3D/VR/AR domain, ontologies can be used to specify data formats and schemes with comprehensive properties and relationships between data elements. In turn, collections of individuals of a knowledge domain, including their properties and relationships between them are referred to as *knowledge bases* [29]. Knowledge bases consist of *statements* about particular objects using classes and properties that have been defined in ontologies. Hence, in the 3D/VR/AR domain, knowledge bases can be used to represent individual 3D scenes and objects.

The Resource Description Framework Schema (RDFS) [37] and the Web Ontology Language (OWL) [34] are languages for building statements in RDF-based ontologies and knowledge bases. In turn, SPARQL [35] is the most widely used query language to RDF-based ontologies and knowledge bases. In contrast to other techniques of content representation, ontologies and knowledge bases enable reasoning over the content. Reasoning leads to inferred tacit (implicit) statements on the basis of statements explicitly specified by the authors. These, in turn, represent implicit content properties.

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The overall knowledge obtained from reasoning can be subject to semantic queries. For instance, connections between 3D objects that form hierarchies in scenes can be subject to reasoning and querying about the scenes' complexity. Similarly, position and orientation interpolators in a 3D scene can be subject to reasoning and querying about the motion categories of objects (linear, curved, rotary, etc.). A semantically represented 3D piston engine can be subject to reasoning to infer and query about its type on the basis of the cylinder arrangement (in-line, multi-row, star or reciprocating).

A number of approaches use semantic web technologies to improve creation, representation and processing of various types of media, including text, images, audio and video. However, comprehensive standardized solutions for semantic creation, representation and processing of 3D content are yet to be developed. This gap is the major obstacle for integration and wide dissemination of VR and AR on the Web.

The main contribution of this paper is the Semantic Web3D approach developed by the X3D Semantic Web Working Group [42], which is a part of the Web3D Consortium. The approach enables ontology-based representation of 3D content on top of the available 3D technologies, including 3D formats. The representation includes different levels of specificity: 3D-specific and domain-specific knowledge. At every level, different classes, objects and properties may be used. The 3D-specific level is constituted by the X3D Ontology, which is a semantic counterpart to the Extensible 3D (X3D) [41]. X3D is a widely used standardized 3D format (ISO/IEC 19775[1]) for web-based applications. It has been developed by the Web3D Consortium as the successor to the Virtual Reality Modeling Language (VRML) [40]. The domain-specific level can be described using arbitrary domain ontologies, e.g., pertaining to cultural heritage, medicine, design, engineering or e-commerce. Ontologies at both levels are linked by mappings. The Semantic Web3D has the following advantages over the previous approaches to semantic 3D representation:

1. It is strictly integrated with leading standardized 3D web technologies by an automatic transformation of the X3D format to the X3D Ontology, which is the foundation of our approach.

2. It covers a comprehensive and up-to-date set of 3D components and properties, including geometry, structure, presentation and animation, since it is generated from X3D.

3. It combines 3D-specific semantics with domain-specific semantics, thereby being applicable to arbitrary areas. Semantic querying, reasoning and processing of 3D content can be performed for both: inherent 3D components and properties (understandable to technical users) as well as domain components and properties (related to a particular usage of the approach and understandable to domain experts).

[1]https://www.iso.org/standard/60760.html

The remainder of this paper is structured as follows. Section 2 provides an overview of the current state of the art in semantic representation of 3D content. In Section 3, we overview the Semantic Web3D approach. The X3D Ontology, which is a key element of the approach, is presented in Section 4. Examples of queries utilizing the ontology are discussed in Section 5. Finally, Section 6 concludes the paper and indicates possible future research.

2. RELATED WORKS

Several works have been devoted to the use of ontologies for 3D content representation. A comparison of such solutions is presented in Table 2. The 3D and domain specificity levels are almost equally addressed by the ontologies. The ontologies also enable representation of different features of 3D content, such as geometry, structure, appearance and animation. In most cases, only some content features are represented by a single ontology. All the ontologies enable representation of 3D structure, in particular spatial relations and hierarchies between 3D objects. Only one third of the ontologies support representation of animation, making it the least covered feature. Five ontologies enable representation of all content features. An extensive comparison of 3D content representations has been presented in [18].

The available solutions have the following limitations:

1. They are not integrated with 3D formats. It hinders transformation between knowledge bases, which can be used for reasoning and querying, and 3D scenes, which can be rendered using available browsers.

2. They do not combine 3D and domain specificity levels. This hinders the use of content by average users and domain experts who are not IT specialists.

3. They do not cover important areas adhering to 3D representation such as humanoid animation, geospatial data, CAD, printing and scanning, do they integrate with separate formats designed for such areas.

3. THE SEMANTIC WEB3D APPROACH

The main contribution of this paper is the Semantic Web3D approach, which is an extension of the approach proposed in [39]. The Semantic Web3D encompasses a queryable ontology-based 3D content representation, which enables creation, modification and analysis of 3D content (Fig. 1). The representation is described in Section 3. Semantic queries possible with the proposed representation are discussed in Section 3.2. In Section 3.3, we analyze the possible use contexts of the Semantic Web3D, which determine new research and application areas, and provide the main motivations for the further development of the approach.

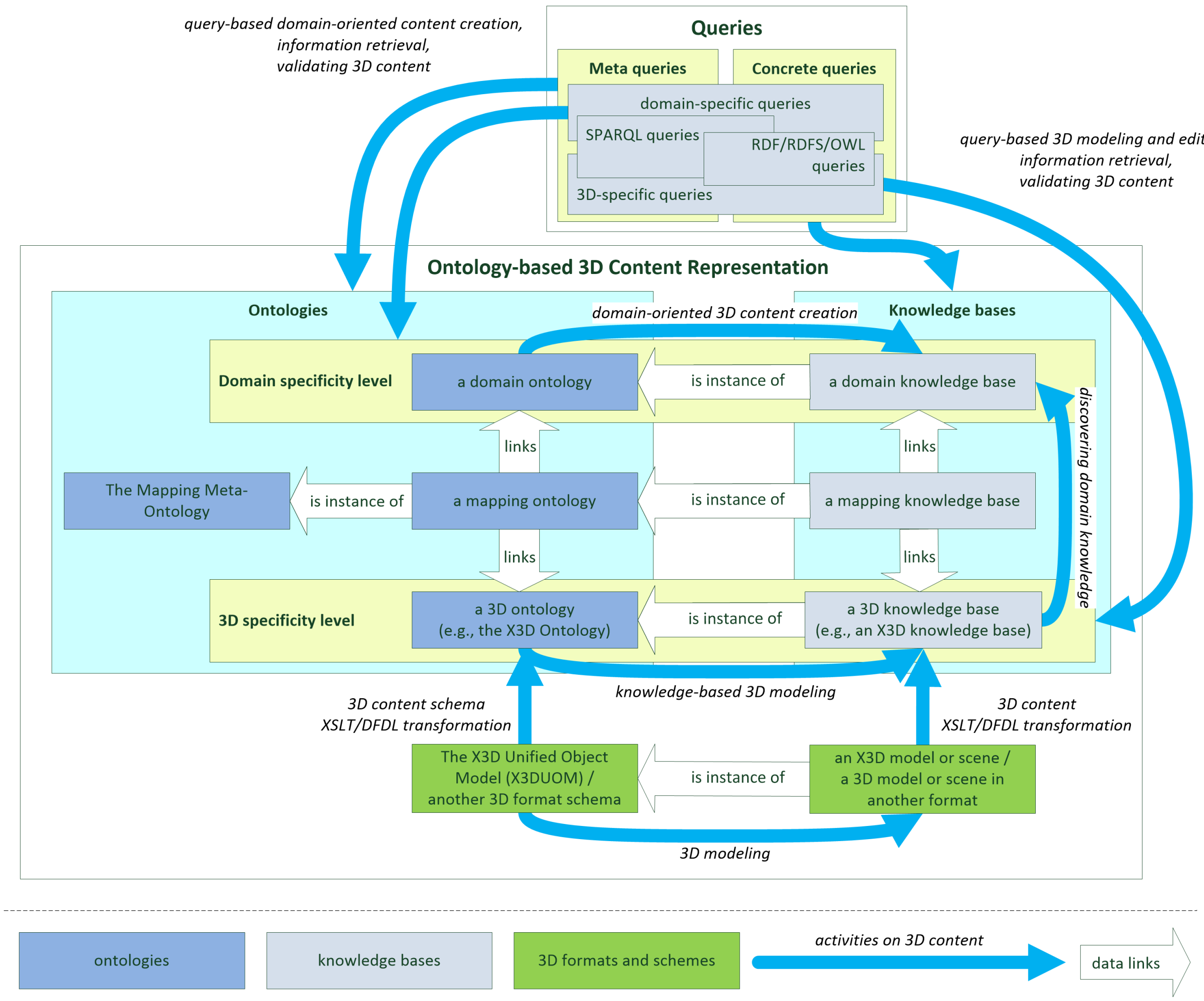

Fig. 1. The Semantic Web3D approach.

Table 1. Comparison of 3D ontologies

Ontology	Specificity level 3D	Specificity level domain	Geom.	Struct.	Appear.	Anim.
[9]	✓	✓	✓	✓	✓	
[1, 30]	✓		✓	✓	✓	✓
[20]	✓		✓	✓	✓	✓
[21]	✓		✓	✓	✓	✓
[26]		✓		✓		
[7]		✓		✓		
[11]	✓		✓	✓		
[10]	✓		✓	✓		✓
[22]		✓		✓		
[33]	✓		✓	✓	✓	
[5]		✓		✓		
[46]		✓		✓	✓	
[14]	✓		✓	✓	✓	✓
[15, 16]		✓		✓	✓	
[24, 28]	✓		✓	✓	✓	✓
[25]	✓			✓		
[12]		✓	✓	✓		
[31]		✓		✓	✓	
[23]		✓		✓	✓	
[27]		✓		✓	✓	
[13, 17]		✓		✓		✓

3.1. Ontology-Based 3D Content Representation

The ontology-based 3D content representation, which is the main element of the Semantic Web3D, is a stack of ontologies and knowledge bases. Ontologies specify 3D content schemes at different levels of specificity, whereas knowledge bases specify 3D models and scenes in line with the ontologies. The representation includes two levels of specificity: the 3D-specific level and the domain-specific level.

1. **The 3D-specific level** uses classes, objects and properties that are related to 3D content, including geometry (e.g., vertices, edges and faces), structure (e.g., hierarchy of objects), appearance (e.g., textures and materials) and animation (e.g., event generators and interpolators). 3D-specific classes and properties are defined in a *3D ontology*, which has been generated from a 3D format schema. So far, we have automatically generated the *X3D Ontology* from the *X3D Unified Object Model* (X3DUOM) using an XSL

transformation (cf. Section 4). The ontology is a counterpart to the X3D format, and consists of classes and properties that are equivalents of X3D elements and attributes. Hence, the X3D Ontology can be suited to a wide range of practical 3D applications, including humanoid animation, geospatial visualization, CAD, printing and scanning. Also other 3D ontologies for different formats can be used at this specificity level. 3D ontologies are intended to be an augmentation of available 3D formats (implemented by 3D browsers) with reasoning and queries. However, in some cases, it may be useful to treat ontologies as independent (semantic) 3D formats directly processable by (semantic) 3D browsers (cf. Section 3.3/9). 3D ontologies can be subject to 3D-specific *meta-queries* (cf. Section 3.2) for *information retrieval* (cf. Section 3.3/6).

   Collections of information about particular 3D models and scenes specified using classes and properties defined in a 3D ontology are referred to as *3D knowledge bases*. 3D knowledge bases may be created by content authors within *knowledge-based 3D modeling* (cf. Section 3.3/1), or automatically generated from 3D models and scenes encoded in a textual or binary 3D format, using the Data Format Description Language (DFDL) [6] (cf. Section 3.3/8). 3D knowledge bases can be subject to 3D-specific *concrete queries* (cf. Section 3.2) for *query-based 3D modeling, editing* and *information retrieval* (cf. Section 3.3/3 and 6).

2. **The domain-specific level** uses classes, objects and properties that are related to an arbitrary domain, which is determined by a particular use case of the approach. For instance, in cultural heritage, classes may correspond to different artifacts (weapons, armors, decorations, etc.), while properties can describe features of the artifacts (types of swords, materials used to make jewelry, etc.). Domain classes and properties are defined in a *domain ontology*, which is determined by a particular Semantic Web3D application. Domain ontologies can be subject to domain-specific *meta-queries* (cf. Section 3.2) for *information retrieval* (cf. Section 3.3/6).

   Collections of information about particular domain objects and properties that build 3D models and scenes using classes and properties defined in a domain ontology are referred to as *domain knowledge bases*. Domain knowledge bases may be created by content authors within *domain-oriented 3D content creation* (cf. Section 3.3/2) or automatically generated from 3D knowledge bases via *discovering domain knowledge* (cf. Section 3.3/5). Domain knowledge bases can be subject to domain-specific *concrete queries* (cf. Section 3.2) for *query-based 3D modeling, editing* and *information retrieval* (cf. Section 3.3/3 and 6).

Ontologies at both levels of specificity are aligned using *mapping ontologies*. A mapping ontology is a specification of how domain-specific classes and properties are represented by 3D-specific classes and properties. Hence, it enables visualization of domain-specific concepts. A mapping ontology is created by a content author or automatically generated by machine learning techniques within *generating mappings* (cf. Section 3.3/4). A mapping ontology is a specialization of the *Mapping Meta-Ontology*, which defines basic, general concepts for mapping. Classes and properties of a mapping ontology are inherited from classes and properties of the Mapping Meta-Ontology. They are specific to a particular Semantic Web3D application. An individual mapping ontology is used for a distinct pair of a 3D ontology and a domain ontology. Hence, it can be reused for different 3D models and scenes built with these ontologies.

Knowledge bases at both levels of specificity are linked by a *mapping knowledge base*, which is a collection of information about how particular domain-specific objects and properties are represented by particular 3D-specific objects and properties. For such a specification, classed and properties defined in the corresponding mapping ontology are used. Hence, a mapping knowledge base specifies visual representations of particular domain objects in a 3D scene, e.g., cars, exhibits and appliances. It is automatically generated during a *domain-oriented 3D content creation* (cf. Section 3.3/2).

3.2. Queries to the Representation

Possible queries to the ontology-based representation of 3D content may be distinguished in terms of the target dataset type, specificity level, encoding standards used, and initiated activity. These four classifications are orthogonal, i.e. every query fits all of them.

1. Classification of queries in terms of the target dataset type:
   (a) **Meta-queries** are about schemes of 3D models and scenes, e.g., data types of properties of particular 3D components, classes of components for which particular properties are used, specializations and hierarchies of components.
   (b) **Concrete queries** are about particular 3D models and scenes, e.g. the distance between two objects in a scene, the number of objects of a particular class in a scene, the value of an object property.
2. Classification of queries in terms of the specificity level:
   (a) **3D-specific queries** are related to 3D components and properties, e.g., the number of vertices and faces of a model, the period of an animation, the color of a material.
   (b) **Domain-specific queries** are related to a particular domain for which the target model or scene has been created, e.g., the age of a virtual museum exhibition, the species of plants in a virtual garden, the functionality of virtual home appliances.

3. Classification of queries in terms of the encoding standards used:

   (a) **SPARQL queries** are encoded in SPARQL [35], which is the primary query language for ontologies and knowledge bases on the Semantic Web.

   (b) **RDF/RDFS/OWL queries** are knowledge bases combined with the target dataset (ontology or knowledge base) and next, used to accomplish reasoning. RDF, RDFS and OWL-based queries have the same encoding as the target datasets. On the one hand, it makes the solution syntactically more uniform then using SPARQL, and liberates content consumers from applying additional software for query processing. Moreover, it enables to determine the computational properties of the overall dataset, in particular decidability. On the other hand, since RDF, RDFS and OWL are knowledge representation formats but not query languages, they lack some query-specific constructs that are available in SPARQL, e.g., order by, limiting the number of results and selecting only distinct results. In addition, they do not permit numerical operations.

4. Classification of queries in terms of the initiated action:

   (a) **Information retrieval** provides information about 3D models or scenes, e.g., get the coordinates of a shape, get the trajectory of a moving object.

   (b) **Modeling and editing 3D content** creates or modifies 3D models or scenes, e.g., add a shape to a scene, change the trajectory of a moving object.

3.3. Contexts of Use

The queryable ontology-based representation of 3D content enables the following activities related to content creation and analysis (marked by blue arrows in Fig. 1).

1. **Knowledge-based 3D modeling**, which is a 3D modeling process supported by knowledge contained in a 3D ontology. The result of this activity is a 3D knowledge base, which represents models or scenes at the 3D-specific level. The use of a 3D ontology can facilitate modeling of 3D content, e.g., by suggesting components and properties, with data types and ranges, that can be set for a particular object. In contrast to available 3D modeling tools, which provide proprietary implementations of such functions, ontologies can describe such features in a standardized way, while reasoning engines can process such descriptions using standard, well-known algorithms.

2. **Domain-oriented 3D content creation**, within which 3D content is created using a domain ontology with domain-specific classes, objects and properties, without appealing to 3D-specific classes, objects and properties (like in typical 3D modeling). For instance, a marketing expert designs an exhibition of home appliances including stoves, dishwashers and washing machines. In this activity, first, a domain knowledge base, which represents models or scenes at the domain-specific level, is created. Next, due to a mapping ontology, which determines 3D representations of domain concepts, final 3D scenes are generated upon the domain knowledge base.

3. **Query-based 3D modeling and editing**, in which concrete queries are issued by content consumers to create or edit content at different specificity levels—using 3D or domain knowledge bases. Such queries can specify new or modify existing objects and properties, e.g., move an artifact to a museum room with a collection dated to the appropriate historical period.

4. **Generating mappings** may be useful for domain ontologies that have no mapping ontologies linking them to 3D ontologies. Therefore, they cannot be used for domain-oriented content creation, query-based modeling and editing, or information retrieval. However, there are some examples of mapping knowledge bases linking domain knowledge bases to 3D knowledge bases. In such a case, machine learning software can generalize the available examples to produce a mapping ontology. For instance, the availability of multiple examples of 5 regularly arranged shapes may be a prerequisite how a table can be constructed (a countertop and 4 legs).

5. **Discovering domain knowledge** can be useful for 3D knowledge bases that have no associated domain knowledge bases, because have been modeled by content authors (*knowledge-based 3D modeling*—p. 1) or automatically generated from models and scenes encoded in 3D formats (*transforming 3D content*—p. 8). Since this activity requires a mapping ontology, it can follow *generating mappings*.

6. **Information retrieval** is possible from ontologies (about schemes of content) and knowledge bases (about individual models and scenes) at different specificity levels. For example, select positions of emergency vehicles in a virtual city.

7. **Validating 3D content** allows content authors and consumers to automatically verify the correctness of 3D models and scenes at different specificity levels against corresponging 3D and domain ontologies, in particular: the use of appropriate classes as well as data types and cardinality of properties. Content validation can by performed by standard reasoning algorithms for RDF, RDFS and OWL implemented by semantic environments, e.g., plugins to Protégé [2]. For instance, a virtual car must have 4 wheels; the vertices of a mesh must form polygons.

8. **Transforming available 3D content to semantic 3D content**, which is enabled by automatic transformation of 3D

format schemes to 3D ontologies, and automatic transformation of 3D content encoded in the formats to 3D knowledge bases compliant with these ontologies. XSLT can be used to transform XML-based 3D formats and content, e.g., in case of X3D, whereas the Data Format Description Language (DFDL) [6] can be used for any (textual or binary) format and content. This opens new opportunities to convert the available repositories and libraries of 3D content to their semantic equivalents, thus enabling the range of new operations on content described in this section.

9. **Rendering ontology-based 3D scenes** can be done in two ways.

   (a) Maintaining the conformance of 3D ontologies to their underlying 3D formats will enable transformation of 3D knowledge bases (compliant with the ontologies) to 3D scenes encoded in the formats. This will integrate our approach with the currently available technologies and enable 3D visualization with a number of well established, efficient content browsers. However, final 3D content encoded in a 3D format can no longer be subject to reasoning and queries.

   (b) The development of semantic 3D browsers is possible to permit direct visualization of 3D knowledge bases. In such a case, transformation of the content could be implicitly accomplished within a browser, while maintaining the possibility of semantic reasoning and queries over dynamically changing content properties with their temporal values, e.g., the volatile position of an object moving in a 3D scene.

4. THE X3D ONTOLOGY

The X3D Ontology [44], which is an RDF/RDFS/OWL document, is a 3D ontology we have developed for the Semantic Web3D approach. It is the successor to the 3D Modeling Ontology (3DMO) [24]. 3DMO has been developed manually based on the X3D format. Therefore, modifications of the ontology necessary to keep its consistency with new versions of the X3D format were problematic. The goal of the Semantic Web3D is to provide flexible integration of available 3D technologies with semantic web technologies. Hence, the X3D Ontology, as the evolution of 3DMO, is automatically generated from the X3D schema, which is described by the X3D Unified Object Model (X3DUOM).

The X3DUOM is a description of the X3D schema, which is a set of object-oriented interfaces for X3D nodes and fields [45]. The X3DUOM is encoded as an XML document that contains a list of the names of the X3D nodes, interfaces and fields, information about inheritance of the nodes and fields, and the fields data types. This is useful to implement various encodings of X3D as well as bindings to programming languages.

The X3D Ontology is generated using an XSL transformation [43]. A fragment of the XSLT document in the Turtle format is presented in Listing 1. The code transforms X3D XML elements to declarations of individual classes in the ontology. It processes every XML element (line 1) by extracting its `name` attribute (2) and printing it as the subject of a new RDF statement in the ontology. The subject is a new *class* within the local namespace in the ontology (3–4). The predicate in the statement is `a` (5), which is a shorthand notation for `rdf:type`. The object in the statement is `owl:Class` (6). In addition, if the processed XML element has sub-elements with the path `InterfaceDefinition/ Inheritance`, including the `baseType` attribute (7), it is used to specify the superclass of the *class* (8–11).

Listing 1. A fragment of the XSLT document describing transformation of the X3DUOM to the X3D Ontology in Turtle.

```
1  <xsl:template match="*"> <!-- process each element -->
2   <xsl:variable name="elementName" select="@name"/>
3   <xsl:text>:</xsl:text><!-- local namespace -->
4   <xsl:value-of select="$elementName"/>
5   <xsl:text> a </xsl:text>
6   <xsl:text>owl:Class</xsl:text>
7   <xsl:if test="(string-length(InterfaceDefinition/
        Inheritance/@baseType) > 0)">
8    <xsl:text> ;&#10; </xsl:text><!-- new line -->
9    <xsl:text>rdfs:subClassOf </xsl:text>
10   <xsl:text>:</xsl:text><!-- local namespace -->
11   <xsl:value-of select="InterfaceDefinition/Inheritance/
        @baseType"/>
12  </xsl:if>
13  ...
14 </xsl:template>
```

An example of an X3DUOM fragment transformed using the XSLT document is presented in Listing 2. Like every element, `Shape` (line 1) is transformed to a class, while information about the inheritance of the `Shape` node (its `baseType`, line 3) is transformed to the superclass specification. The resulting statements are:

```
:Shape a owl:Class ; rdfs:subClassOf :X3DShapeNode .
```

Listing 2. A fragment of the X3DUOM document describing the X3D Shape node.

```
1 <ConcreteNode name="Shape">
2  <InterfaceDefinition specificationUrl="https://www.web3d
       .org/documents/specifications/19775-1/V3.3/Part01/
       components/shape.html#Shape">
3   <Inheritance baseType="X3DShapeNode"/>
4     ...
5  </InterfaceDefinition>
6 </ConcreteNode>
```

Fragments of the generated hierarchies of classes as well as object and datatype properties of the X3D Ontology visualized in the Protégé ontology editor are depicted in Fig. 2.

Another XSLT document has been developed to enable transformation of X3D scenes to X3D knowledge bases compliant with the X3D Ontology.

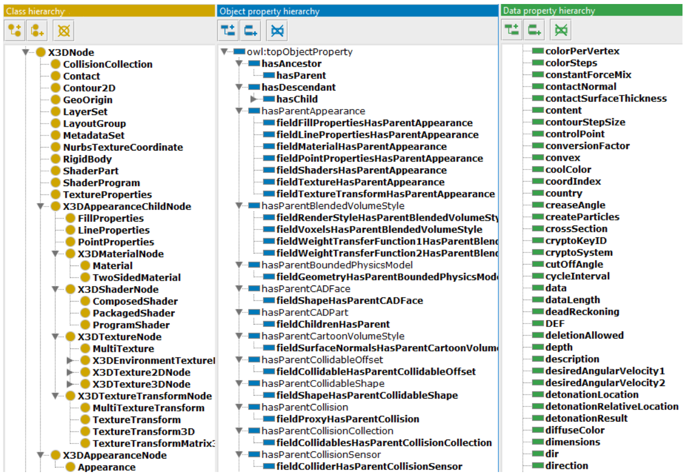

Fig. 2. Hierarchies of classes as well as object and datatype properties of the X3D Ontology presented in Protégé.

5. EXAMPLE

In this section, we present an example of transforming an X3D scene to an X3D knowledge base compliant with the X3D Ontology. The scene presents the San Carlos Cathedral in Monterey, CA, USA[2] (Fig. 3).

Listing 3 includes a fragment of the generated X3D knowledge base, covering some scene properties as well as the altar. The scene has a background with a sky color represented by an RDF list of values (lines 3–6). In addition, there is a transform node applied to a shape that is a wooden element of the altar (7–11). The shape of the element is determined by a box with a given size (12–14). Like sky color, translation and size are also represented by RDF lists. In addition, the element has appearance with an image texture (15–18).

Listing 3. A fragment of an X3D knowledge base describing the altar in the San Carlos Cathedral.

```
1  # Prefixes: 'x3do', ':', 'rdf' and 'owl' indicate: the X3D
       Ontology and knowledge base as well as RDF and OWL.
2
3  :scene rdf:type owl:NamedIndividual , x3do:Scene .
4  :scene x3do:hasBackground :background .
5  :background rdf:type owl:NamedIndividual, x3do:Background;
6   x3do:skyColor (0.7216 0.8 0.9922).
7  :scene x3do:hasTransform :Colonna1 .
8  :Colonna1 rdf:type owl:NamedIndividual , x3do:Transform ;
9   x3do:translation (0.7 0 -0.7) .
10 :Colonna1 x3do:hasShape :woodenElement1 .
11 :woodenElement1 rdf:type owl:NamedIndividual , x3do:Shape.
12 :woodenElement1 x3do:hasBox :woodenElement1Box .
13 :woodenElement1Box rdf:type owl:NamedIndividual, x3do:Box;
14  x3do:size (0.4 1.2 0.4) .
15 :woodenElement1 x3do:hasAppearance :WoodAppearance .
16 :WoodAppearance rdf:type owl:NamedIndividual , x3do:
      Appearance .
17 :WoodAppearance x3do:hasTexture :Wood .
18 :Wood rdf:type owl:NamedIndividual , x3do:ImageTexture ;
      x3do:url ".../Wood.jpg" .
```

[2]https://x3dgraphics.com/examples/X3dForAdvancedModeling/SanCarlosCathedral/SanCarlosCathedralIndex.html

Fig. 3. An X3D model of the San Carlos Cathedral[2] (Monterey, CA, USA): a view from outside and the altar.

Every X3D knowledge base can be subject to semantic queries. The following SPARQL query provides the number of shapes composing the altar. The result of the query is: `14`.

```
SELECT (count(distinct ?shape) as ?num) WHERE {
 ?shape rdf:type x3do:Shape . }
```

The following query provides the paths of all textures used within the scene. The result is the wood texture: `.../Wood.jpg` (cf. Listing 3, line 18).

```
SELECT ?textureUrl WHERE {
 ?x x3do:hasTexture ?texture .
 ?texture x3do:url ?textureUrl . }
ORDER by ASC(?textureUrl)
```

The following query retrieves the color of the sky used in the scene. The result is the following list of RGB values: `0.7216 0.8 0.9922` (cf. Listing 3, line 6).

```
SELECT ?skyColorListVal WHERE {
 ?background rdf:type x3do:Background ;
  x3do:skyColor/rdf:rest*/rdf:first ?skyColorListVal . }
```

6. CONCLUSIONS AND FUTURE WORKS

In this paper, we have presented the concept of the Semantic Web3D approach, which has been developed by the X3D Semantic Web Working Group. The approach enables comprehensive ontology-based representation of 3D content at different specificity levels, which integrates with available 3D technologies. This sets directions to a variety of new 3D/VR/AR applications in different domains.

The primary implementation of the approach described in the paper encompasses the XSL transformation of the X3DUOM to the X3D Ontology, the XSL transformation of X3D scenes to X3D knowledge bases as well as testing queries to the ontology and knowledge bases. We plan to continue the development of DFDL-based transformations of other textual and binary 3D formats, tools for semantic 3D scene validation as well as semantic 3D browsers to directly render 3D knowledge bases.

7. REFERENCES

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