X3D Ontology for Querying 3D Models on the Semantic Web

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ABSTRACT

The Semantic Web offers significant capabilities that transform the current Web into a global knowledge base including various cross-linked multimedia content with formal descriptions of its semantics understandable to humans and processable by computers. Content on the Semantic Web can be subject to reasoning and queries with standardized languages, methods and tools, which opens new opportunities for collaborative creation, use and exploration of web repositories. However, these opportunities have not been exploited so far by the available 3D formats and modeling tools, which limits the possibilities of search and reuse of 3D content as part of the Semantic Web. This work contributes a semantic development pipeline of the X3D Ontology, with corresponding conversion of X3D models into triple forms suitable for formal query. The ontology design reflects experience accompanying the development of the Extensible 3D (X3D) Graphics International Standard, in particular, the X3D Unified Object Model (X3DUOM). This approach combines semantic and syntactic elements of X3D models and metadata to support integration with the Semantic Web. The pipeline enables automatic generation of the X3D Ontology, thereby providing an up-to-date 3D representation with semantics during X3D specification development. By extending commonplace model conversions from other formats to X3D, the ontology presents the potential to enable integration of most forms of 3D content with the Semantic Web.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Mixed / augmented reality**; • **Computing methodologies → Virtual reality**; **Mixed / augmented reality**; • **Information systems → Multimedia content creation**; **Semantic web description languages**; *Multimedia databases.*

KEYWORDS

X3D Ontology, Web3D, Semantic Web, Semantic 3D, X3DUOM

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1 INTRODUCTION

Web-based 3D graphics as well as virtual reality (VR) and augmented reality (AR) environments are becoming increasingly popular in various application domains such as marketing, tourism, medicine, prototyping, and cultural heritage. Development of web-based VR and AR has been enabled by various 3D formats, including the Virtual Reality Modeling Language (VRML) [W3C 1995] and Extensible 3D (X3D) [Brutzman and Daly 2007; W3C 2020; X3D Working Group, Web3D Consortium 2020], programming libraries (e.g., WebGL [The Khronos Group 2020] and WebXR [W3C 2020]) and game engines (e.g., Unreal [Games 2020] and Unity [Technologies 2020]). Various applications of 3D on the Web are fostered by high network bandwidth as well as affordable presentation and interaction devices, such as headsets and motion tracking systems. As the dissemination of 3D content on the Web growths, the issue of integrating 3D/VR/AR systems with other prominent web technologies emerges.

The Semantic Web is one of the most influential and promising trends in the current evolution of the Web [Berners-Lee et al. 2001]. It is built upon well-established standards related to such elements as resource identification, syntax and schemes for web resources. In combination with XML structure and XML Schema validation, as well as semantic data models and languages based on description logics, powerful languages are available for knowledge representation, reasoning and query.

The Semantic Web is a global knowledge base that links structured content with formal descriptions of content semantics. Semantic descriptions are enabled by standards of structured data representation, such as the Resource Description Framework [W3C 2014a], the Resource Description Framework Schema [W3C 2014b] and the Web Ontology Language [W3C 2012]. The standards are conceptually based on description logics [Krötzsch et al. 2012] and permit creation of ontologies, which are *explicit specifications of conceptualization* for a particular domain, encompassing domain-specific classes, properties and relations between them [Gruber 2009; Sikos 2017b]. Ontology-based descriptions of content can be subject to automated reasoning and queries. Reasoning is the process of acquiring properties of content that have not be explicitly specified but may be inferred from explicitly specified properties. In turn, queries enable focus on content properties relevant to a particular use case and filter out the irrelevant properties. For instance, 3D objects' hierarchies in scenes can be subject to reasoning and queries about the scenes' complexity. Position and orientation interpolators in 3D scenes can be subject to reasoning and queries about the categories of objects' motion (e.g., linear, curved and rotary).

However, the opportunities above are still not used by 3D, VR and AR environments as the available 3D technologies, including 3D formats, graphics programming libraries and game engines have not been intended for integration with the Semantic Web. It limits possibilities for search and reuse of 3D models and scenes in web repositories, reasoning on 3D content, and analyzing 3D content with complex and precise queries.

The main contribution of this paper is the pipeline that enables creation and maintenance of the X3D Ontology. The pipeline has been devised by the X3D Semantic Web Working Group [Web3D Consortium 2020b], which is a part of the Web3D Consortium. The X3D Ontology, which results from the pipeline, allows for representation of interactive 3D content based on description logics, using the semantic web standards. The standards permit formal semantics, including classes of and relations between various 3D components, such as geometry, materials, spatial properties and animations. The formal semantics offers new opportunities in comparison to the available non-semantic 3D formats and programming languages. Reasoning on ontology-based 3D content enables analysis of not only the components and properties that have been explicitly specified by the authors but also the components and properties that are implied by the former ones. For instance, every 3D object whose geometry comprises a number of faces in a particular range can be classified as one with a simple, medium, or complex geometry by automated reasoning—without any actions from the content authors.

In addition to the pipeline, the focus is applied to the idea of queryable 3D models and scenes. A continuing design goal is to show that general representations and semantic queries of geometric models can be accomplished using formal terms of reference, the X3D Ontology for the Semantic Web, and conversion mappings for all manner of 3D formats into X3D Graphics International Standard. Although multiple converters are available for diverse 3D formats, the available solutions do not enable reasoning and querying 3D models and scenes. This functionality is crucial in artificial intelligence and knowledge representation systems, but it has not been applied to 3D content representation so far. The available 3D ontologies are used like typical 3D formats providing schemes for 3D content. They offer a syntax but do not benefit from description logics solutions that underlie the Semantic Web and ontologies—formal semantics. This is the gap we want to fill in the paper.

A variety of classes of and relations between 3D content components of the ontology are counterparts to the elements and attributes of X3D. X3D is a widely used standardized 3D format for web-based 3D environments. It has been developed by the Web3D Consortium as the successor to VRML. Our approach is strictly linked to X3D via an automatic transformation of the format to the ontology, ensuring a comprehensive and up-to-date set of 3D components and properties. It is a significant advantage over the other 3D ontologies, which are not based on particular continuously developed 3D formats.

The remainder of this paper is structured as follows. The next section provides an overview of the current state of the art in the semantic web standards and ontologies for 3D content. The X3D Ontology, which is an essential element of the approach, and the ontology development pipeline are summarized in detail in Section 3. A discussion and examples of queries utilizing the ontology follow in Section 4. Finally, the paper provides conclusions and indicates possible future research in Section 5.

2 RELATED WORK

2.1 Semantic Web

The Semantic Web is an emerging trend influential to a growing number of systems in different domains. It is currently one of the leading approaches to knowledge representation offering well-established standards with thoroughly investigated computational properties [W3C 2012]. Content descriptions based on the Semantic Web are human-readable and computer-processable. Therefore, semantic web standards are chosen as the foundation of this approach.

The primary standards used to represent content of any type on the Semantic Web are the Resource Description Framework (RDF) [W3C 2014a], the RDF Schema (RDFS) [W3C 2014b] and the Web Ontology Language (OWL) [W3C 2012]. RDF is a data model based on statements in the form of *(subject, predicate, object)* triples. In a statement, the *subject* is what we describe, the *predicate* is a property of the subject, and the *object* is a predicate value, a descriptor, or another entity that is in a relationship with the subject. RDFS and OWL are languages built upon RDF, providing even-higher expressiveness: classes and properties with relations and hierarchies, which enable comprehensive description of content.

These standards permit design of ontologies, which are *specifications of conceptualization* [Gruber 2009] for a domain. Ontologies are *formal conceptualization of the intended semantics of a knowledge domain or common-sense human knowledge, i.e. an abstract, simplified view of the world represented for a particular domain* [Sikos 2017b]. Ontologies enable knowledge representation, which can be expressed using statements that belong to three groups. *Terminological knowledge* (TBox) describes conceptualization, meaning a set of concepts and relations between them. *Relational knowledge* (RBox) describes hierarchies and properties of relations. *Assertional knowledge* (ABox) describes facts about individuals (objects) using concepts formalized in TBox and RBox. Ontologies may describe arbitrary objects as well as classes and properties of objects, which makes them a general solution for content description across diverse applications and domains. Ontologies constitute the foundation of the Semantic Web. Ontologies developed with RDF, RDFS and OWL can be queried using SPARQL [W3C 2013], which is the primary query language for the Semantic Web.

2.2 Ontologies for 3D Content

Several works have considered the use of ontologies for 3D content representation. A comparison of such solutions is presented in Table 1. Domain-specific levels of 3D expressiveness are almost equally addressed by the ontologies, albeit with different terms of reference. 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 [Flotyński and Walczak 2017b].

The available solutions have the following limitations:

Table 1: Comparison of 3D ontologies. (Bille, W., et al., 2004)—[Bille et al. 2004]; (AIM@SHAPE), (Spagnuolo, et al., M., 2008)—[aim 2017; Spagnuolo and Falcidieno 2008]; (Gutierrez, et al., M., 2007)—[Gutiérrez et al. 2007]; (Kalogerakis, E., et al., 2006)—[Kalogerakis et al. 2006]; (Pittarello, F., et al., 2006)—[Pittarello and De Faveri 2006]; (Attene, M., et al., 2007)—[Attene et al. 2007]; (Floriani, L., et al., 2007)—[De Floriani et al. 2007]; (Chu, Y., et al., 2012)—[Chu and Li 2012]; (Kapahnke, P., et al., 2010)—[Kapahnke et al. 2010]; (Vasilakis, G., et al., 2010)—[Vasilakis et al. 2010]; (Albrecht, S., et al., 2011)—[Albrecht et al. 2011]; (Wiebusch, D., et al., 2012)—[Wiebusch and Latoschik 2012]; (Flotyński, J., et al., 2013)—[Flotyński and Walczak 2013; Flotyński and Walczak 2013b]; (Flotyński, J., et al., 2014, 2016)—[Flotyński and Walczak 2013a; Flotyński and Walczak 2016]; (Sikos, L.F., 2017)—[Leslie F. Sikos [n.d.]; Sikos 2017a]; (Perez-Gallardo, Y., et al., 2017)—[Perez-Gallardo et al. 2017]; (Drap, P., et al. 2017)—[Drap et al. 2017]; (Trellet, M., et al., 2018)—[Trellet et al. 2018]; (Kontakis, K., et al., 2017)—[Kontakis et al. 2014]; (Radics, P.J., et al., 2015)—[Radics et al. 2015]; (Flotyński, J., et al., 2017)—[Flotyński et al. 2017; Flotyński and Walczak 2014; Flotyński and Walczak 2017a]

Ontology	Specificity level		Geom.	Struct.	Appear.	Anim.
	3D	Domain				
(Bille, W., et al., 2004)	✓	✓	✓	✓	✓	
(AIM@SHAPE),(Spagnuolo, M., et al., 2008)	✓		✓	✓	✓	✓
(Gutierrez, M., et al., 2007)	✓		✓	✓	✓	✓
(Kalogerakis, E., et al., 2006)	✓		✓	✓	✓	✓
(Pittarello, F., et al., 2006)		✓		✓		
(Attene, M., et al., 2007)		✓		✓		
(Floriani, L., et al., 2007)	✓		✓	✓		
(Chu, Y., et al., 2012)	✓		✓	✓		✓
(Kapahnke, P., et al., 2010)		✓		✓		
(Vasilakis, G., et al., 2010)	✓		✓	✓	✓	
(Albrecht, S., et al., 2011)		✓		✓		
(Wiebusch, D., et al., 2012)		✓		✓	✓	
(Flotyński, J., et al., 2013)	✓		✓	✓	✓	✓
(Flotyński, J., et al., 2014, 2016)		✓		✓	✓	
(Sikos, L.F., 2017)	✓		✓	✓	✓	✓
(Perez-Gallardo, Y., et al., 2017)	✓			✓		
(Drap, P., et al. 2017)		✓	✓	✓		
(Trellet, M., et al., 2018)		✓		✓	✓	
(Kontakis, K., et al., 2017)		✓		✓	✓	
(Radics, P.J., et al., 2015)		✓		✓	✓	
(Flotyński, J., et al., 2017)		✓		✓		✓

(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. It 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, 3D printing, 3D scanning, medical records, building models and cultural heritage, nor do they integrate with separate formats designed for such diverse domains.

Recent work in International Standards Organization (ISO) is considering general Geometry Topology Ontology Feasibility [ISO TC184 SC4 WG12 T1 2020] to good effect. This ontology is intended *to consider the way in which geometry and topology can be handled with a Semantic Web environment. Many industrial applications are now being developed for this environment, and many of these require the capability of geometric and topological modelling representations.* Strictly defined geometric and topological terms of reference are represented equivalently in Web Ontology Language (OWL). This work is expected to provide a common conceptual basis and corresponding geometric equivalence relationships across a wide range of 3D formats and structured vocabularies.

Such work holds fundamental importance. Future work includes writing geometric relationships for X3D that use the same OWL terms and concepts. In this manner, a general path for geometric query will continue to evolve in a formally defined manner.

3 X3D ONTOLOGY

The X3D Ontology [Web3D Consortium 2020a] is an RDF/RDF-S/OWL document composed of arbitrarily ordered TBox, RBox and ABox triples. The ontology specifies classes (in the TBox) and relations (in the RBox) of 3D content components describing geometry, structure, space, appearance, and animation of 3D content. The goal of the ontology is to provide flexible integration of the X3D standard with semantic web technologies. Hence, the X3D Ontology is automatically generated from the X3D XML Schema described by the X3D Unified Object Model (X3DUOM). Production relationships are illustrated in Fig. 1.

The X3DUOM [Web3D Consortium 2019b] is a complete set of object-oriented interfaces for X3D nodes and fields [X3D Working Group, Web3D Consortium 2020]. 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 each field's data type and accessType. This complete set information is useful to implement various encodings of X3D as well as bindings to various programming languages.

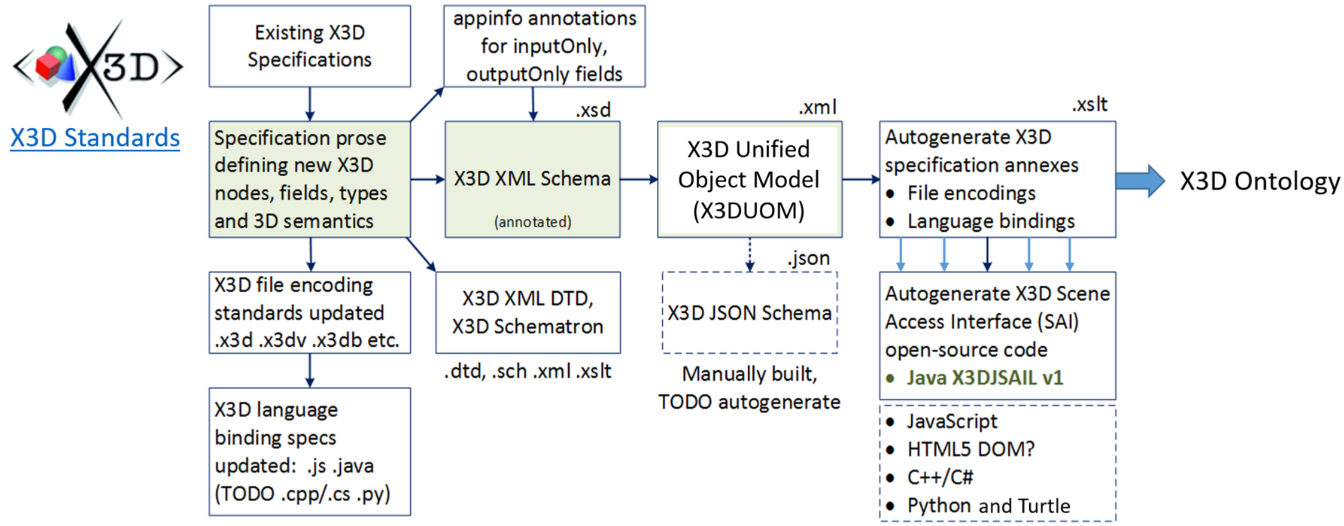

Figure 1: X3D specification [X3D Working Group, Web3D Consortium 2020] is used to annotate X3D XML Schema and to autogenerate both X3DUOM [Web3D Consortium 2019b] and X3D Ontology [Web3D Consortium 2020a].

As shown in Listings 1 and 2 and Fig. 2, the X3DUOM is further processed using an XSL transformation stylesheet [Web3D Consortium 2019a] to generate the X3D Ontology itself. Utilizing well-defined design patterns ensures that ontology definitions are consistently constructed in every case. The rigor of this approach has further improved consistency of the X3D specification design [X3D Working Group, Web3D Consortium 2020].

The X3D ontology contains the full set of data types and scene graph parent-child relationships available in X3D, which permits query of any X3D model. X3D Ontology creation also includes a number of additional derivative properties to facilitate query of parent-child relationships such as `hasChild`, `hasGeometry`, etc. As experience grows with the use of SPARQL queries on X3D models, a growing set of such relationships are expected to be derived (both explicitly and implicitly) in support of rich reasoning capabilities for X3D models.

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

```
<xsl:template match="*"> <!-- process each element -->
  <xsl:variable name="elementName" select="@name"/>
  <xsl:text>:</xsl:text><!-- local namespace -->
  <xsl:value-of select="$elementName"/>
  <xsl:text> a </xsl:text>
  <xsl:text>owl:Class</xsl:text>
  <xsl:if test="(string-length(InterfaceDefinition/
       Inheritance/@baseType) > 0)">
    <xsl:text> ;&#10; </xsl:text><!-- new line -->
    <xsl:text>rdfs:subClassOf </xsl:text>
    <xsl:text>:</xsl:text><!-- local namespace -->
    <xsl:value-of select="InterfaceDefinition/Inheritance/
         @baseType"/>
  </xsl:if>
  ...
</xsl:template>
```

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

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

```
:WorldInfo a owl:Class ;
  rdfs:subClassOf :X3DInfoNode ;
  rdfs:label "WorldInfo contains a title and simple persistent
metadata information about an X3D scene. This node is strictly
for documentation purposes and has no effect on the visual
appearance or behaviour of the world." .
:info a owl:DatatypeProperty ;
  rdfs:subPropertyOf :accessTypeInputOutput ;
  rdfs:domain :WorldInfo ;
  rdfs:range :MFString .
:title a owl:DatatypeProperty ;
  rdfs:subPropertyOf :accessTypeInputOutput ;
  rdfs:domain :WorldInfo ;
  rdfs:range :SFString .
:hasParent a owl:ObjectProperty ;
  owl:inverseOf :hasChild;
  rdfs:subPropertyOf :hasAncestor ;
  dc:description "X3D element (node or statement) has a parent
element" .
:Scene a owl:Class ;
  rdfs:label "Scene is the implicit root node of the X3D scene
graph."
```

Figure 2: An excerpt of the X3D Ontology demonstrating its full compliance with X3DUOM, RDFS and OWL.

4 SEMANTIC X3D CONTENT AND QUERIES

Yet another stylesheet is utilized to facilitate X3D query. The X3DToTurtle.xslt is used for conversion of any X3D model (in the XML syntax) to a TTL model (Terse Triple Language—Turtle). Example queries can then be applied to each of the 4000 open-source models in the X3D Example archives, facilitating regression testing and regular improvement. Example conversion of HelloWorld.x3d with corresponding SPARQL query results follow in Fig. 3 and 4.

```
:X3D a owl:NamedIndividual, x3do:X3D ;
  x3do:hasHead :head ;
  x3do:hasScene :Scene ;
  x3do:profile 'Immersive' ;
  x3do:version '3.3' ;
  x3do:noNamespaceSchemaLocation
'http://www.web3d.org/specifications/x3d-3.3.xsd' .

:Scene a owl:NamedIndividual, x3do:Scene ;
  x3do:hasParent :X3D ;
  x3do:hasChildren :WorldInfo_2_1, :Background_2_2, :Group_2_3 .

:WorldInfo_2_1 a owl:NamedIndividual, x3do:WorldInfo ;
  x3do:hasParent :Scene ;
  x3do:title 'Hello World!' .

...
```

Figure 3: An excerpt of the Hello.World.x3d [Don Brutzman 2019] model transformed to the semantic form in RDF/Turtle [Don Brutzman and Jakub Flotyński 2020a].

```
# Prefixes:
PREFIX rdf:  <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX owl:  <http://www.w3.org/2002/07/owl#>
PREFIX xsd:  <http://www.w3.org/2001/XMLSchema#>
PREFIX x3d:  <http://www.web3d.org/specifications/x3d-4.0.xsd#>
PREFIX x3do:
<http://www.web3d.org/specifications/X3dOntology4.0#>

# Query content:
SELECT ?WorldInfoNode ?title ?parentNode
WHERE
{
    ?WorldInfo rdf:type       x3do:WorldInfo ;
               x3do:title     ?title         ;
               x3do:hasParent ?parent .

    BIND (strafter(xsd:string(?WorldInfo),"#") AS ?WorldInfoNode)
    BIND (strafter(xsd:string(?parent),"#")    AS ?parentNode)
}

# Query result:
-------------------------------------------------
| WorldInfoNode   | title          | parentNode |
=================================================
| "WorldInfo_2_1" | "Hello World!" | "Scene"    |
-------------------------------------------------
```

Figure 4: SPARQL query [Don Brutzman and Jakub Flotyński 2020b] against the HelloWorld.ttl model [Don Brutzman and Jakub Flotyński 2020a] reveals scene title, if any.

More advanced queries are now becoming possible. Current work is attempting queries that are not feasible by direct search and require composition of semantic relationships for proper response. Since X3D animation is totally general, any field in a scene graph can be modified to produce behavior changes. Event animation chains produced by ROUTE connections between initiation triggers, TimeSensor clocks animation interpolators, and finally, target-destination fields can be inspected for correct data type and accessType (input/output) relationships. Fig. 5 shows the results.

Subsequent queries are planned to build on these results to further determine whether type, accessType and animation event-chain requirements are met. In turn, queries for partial completions are expected to reveal improperly formed animation chains which ordinarily are only detectable by humans checking for specific behavioral results. Model properties and queries are fully scalable thanks to the fundamental triple design of the Semantic Web.

5 CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed a new approach to integrating interactive 3D content, in the form of X3D models, with the Semantic Web, a prominent trend in the Web evolution. The X3D Ontology enables representation of 3D objects and scenes that is equivalent to the information already found in other X3D file encodings and 3D content formats. However, it is not designed for rendering, but rather for querying and reasoning across various relationships that can occur between general metadata information and 3D content structures. Thereby, it corresponds to the growing need for queryable web repositories of reusable 3D models and scenes. The ontology is firmly connected to the X3D format by the proposed transformation. Thus, any change of X3D can be instantly introduced to the ontology, providing a new, semantic 3D format, which is permanently up-to-date compared to other 3D representation and modeling technologies.

Similar to 3D geometry, regular forms of metadata that exist in other domains (CAD, medicine, heritage, buildings, etc.), partially covered by Web3D Consortium Working Groups, that can be mapped and composed effectively for direct publication in models of interest. This simultaneously enables rendering, cross-linking and queryable informational assets to be made available in a coherent fashion on the Web.

As best practices for publication emerge, and as structured vocabularies holding formal terms of reference become better known, queries about form function and purpose will grow increasingly powerful and commonplace. Design patterns for SPARQL queries hold great value.

Mappings of 3D geometry from numerous domains, applications and file formats can continue to be correlated for common publication interoperability, with the addition of metadata providing informational context. The reverse relationship is becoming possible: mappings between X3D and other forms provide a basis for OWL mappings that potentially enable queries to reach directly into the alternate models.

The semantics of the ontology-based X3D format is strictly determined by the data sources that we use to generate the ontology. In particular, when generating the ontology from XSD, we change the format—from rendering-oriented to reasoning-and query-oriented. When adding X3DUOM to the transformation, we enrich the final semantics with more complex relationships between entities: nodes and attributes of X3D. However, in both cases, we still do not have domain-specific semantics in the generated semantic 3D format, which is a possible future research direction.

parentNode	RouteFound	fromNodeDEF	fromNodeTypeFound	fromField	toNodeDEF	toField
"Scene"	"ROUTE_2_5"	"OrbitalTimeInterval"	x3do:TimeSensor	"fraction_changed"	"SpinThoseThings"	"set_fraction"
"EarthCoordinateSystem"	"ROUTE_2_6_1"	"SpinThoseThings"	x3do:OrientationInterpolator	"value_changed"	"EarthCoordinateSystem"	"set_rotation"
"EarthCoordinateSystem"	"ROUTE_2_6_5"	"ClickTriggerTouchSensor"	x3do:TouchSensor	"touchTime"	"OrbitalTimeInterval"	"startTime"

Figure 5: Another SPARQL query shows correctly formed ROUTE relationships in a scene animation.

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