Ontology-Based Meta Model in Object-Oriented World Modeling for Interoperable Information Access

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***Abstract*—Many systems rely on the integration of environment observations provided by sensor systems to fulfill their tasks. The Object-Oriented World Model (OOWM) is an information fusion architecture allowing to integrate observations from heterogeneous sensing systems and to provide consolidated information to higher level processing modules in a compound system. Both, data integration and the provision of consolidated information require to exchange information in a meaningful and semantic interoperable way. To promote the semantic interoperability in the OOWM, an ontology-based meta model is presented, allowing to structure the knowledge used to represent application domains as well as interface information objects. This meta model defines an upper level ontology for world modeling, which can be extended by specific domain models and facilitates the integration of additional sensor systems. To allow semantic access to OOWM information, the use of OGC Web Feature Services and Sensor Observation Services based on the meta model is proposed.**

***Keywords*-object-oriented world modeling; knowledge representation; ontology; semantic interoperability; WFS; SOS**

I. Introduction

Information on their environment is a prerequisite to the successful operation of many systems that support decision making or even decide autonomously. Nowadays, environment information often is available in considerable quantities, provided by heterogeneous sensing systems. A major challenge for making use of this information is to manage it adequately. Such managing includes tasks like the integration, processing and consolidation of information as well as providing the means to make this information accessible for further analysis and available to stakeholders.

One approach to this task of managing environment information is the use of a world modeling system. World modeling generates a computational representation of a considered environment, both by capturing background information (i.e., general facts) on the application domain and by acquiring current information on the state of the environment based on observations and measurements. An example of such a world modeling system is the Object-Oriented World Model (*OOWM*) [1]. The OOWM is a probabilistic information fusion architecture for managing acquired sensor information. It has been successfully applied to domains like autonomous systems [2], video surveillance [3] and situation assessment [4].

The OOWM is suited for integrating and consolidating observations from heterogeneous sensing systems. It has been designed to act as a central information hub in a compound system and can supply connected modules (like higher level processing or analysis modules) with the information they need. Interoperability on a syntactic as well as on a semantic level is a key issue for such compound systems to function properly. It is needed on the one hand for integrating observations from different sensing systems, as input to the OOMW, and on the other hand, when providing access to the information within the OOWM to higher level processing modules. Currently, much configuration effort and possibly data transformations are needed for integrating additional sensing systems into the OOWM. Concerning information access, though standard-based mechanisms are defined within the OOWM, these mechanisms yet rely on proprietary data models containing only sparse semantics.

To promote semantic interoperability and information exchange to and from the OOWM, this contribution proposes an ontology-based meta model for structuring the background information used to represent an application domain as well as to formalize the information objects necessary for providing semantically enriched access interfaces.

An example of an intelligent system based on the OOWM is the ISR Analytics Architecture [5], a framework for analyzing and accessing information related to the domain of intelligence, surveillance and reconnaissance. Within this architecture, a specialized software layer is responsible for providing observation data from different sources to the OOWM, and software modules from an analytics layer access OOWM information to perform their analyses. Against the background of such compound systems, we present how the proposed ontology can be integrated into state-of-the-art service-oriented interfaces like the Web Feature Service (*WFS*) [6] or the Sensor Observation Service (*SOS*) [7] standardized by the Open Geospatial Consortium (*OGC*).

This paper is structured as follows. Section II gives an

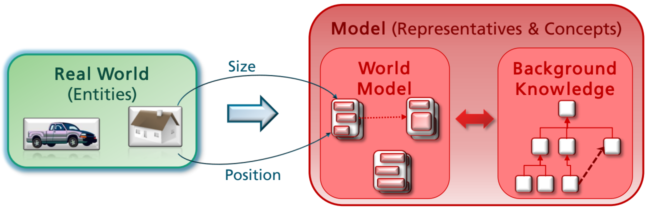

Figure 1. Overview of Object-Oriented World Modeling. Observed real-world entities are represented as objects in the World Model, based on concepts defined in Background Knowledge given as taxonomic structure.

introduction to the OOWM approach. Section III discusses semantic interoperability in world modeling. In Section IV, the proposed meta model ontology is presented in detail. Section V then introduces the web-services based access interfaces to the OOWM and discusses an approach for their model-driven implementation.

II. Object-Oriented World Modeling

The OOWM [1], [2] is a probabilistic data and information fusion framework which allows to represent the current and historic state of a considered real-world domain based on observation data. Intended as a general framework for world modeling, the OOWM is able to integrate observations delivered by heterogeneous sensing systems and can thus be employed in many different application domains. It is designed to serve as a persistent memory structure and information hub, providing higher level processing modules with integrated information.

The OOWM is based on the concept of using observations of entity features (e.g., dynamic features like position or static features like size), to model real-world entities (e.g., objects, persons or abstracta). Observed entities and relations are represented as structured objects in a dynamic World Model. The objects are based on a priori modeled Background Knowledge, which contains the concept classes representing the entities and relationships occurring in an application domain. This Background Knowledge is the basis for evaluating, classifying and completing information derived from observations as well as for querying the World Model for information about observed entities. Figure 1 summarizes the Object-Oriented World Modeling approach.

For managing and updating the information stored in the OOWM, information processing based on the Bayesian methodology is employed. Information about attribute values of observed entities and the existence of relations is represented by probability distributions, thus allowing the OOWM to explicitly treat uncertainties e.g. arising from sensor measurements. Using the Bayesian methodology, these values can be subject to probabilistic information processing, including updates and fusion with related or newly acquired information, prediction in time, aging or further processing within higher level modules. This information processing is supported by probabilistic data association algorithms like the JIPDA [8], relying on the spatial position of observations and entities for data association. The classification of observed entities based on their attribute values, i.e., the mapping of an entity representation to a concept class, can be handled within the Bayesian methodology as well.

All information processing within the OOWM is applied on the basis of a discrete model of time. For each discrete point of time, attribute values and relations get stored in a state-of-the-art database, thus allowing to access domain state information for past points of time. Such historic information is needed for traceability of information states, for example in applications where decisions are based on a certain information set available up to this point of time.

III. Semantic Interoperability in World Modeling

Interoperability is a key issue to systems like the OOWM which integrate heterogeneous observations and provide information to various higher level processing modules. For information exchange, syntactic interoperability relies on the definition of common data types and interfaces. Semantic interoperability builds up on these definitions and aims at allowing a meaningful interpretation of exchanged information by defining a semantic information model, e.g., an ontology. Within the OOWM, XML Schema definitions or lightweight concept hierarchies are employed to ensure syntactic interoperability, specifying the data structures used to represent domain entities as well as their observations. An expressive ontology supporting semantic interoperability has not yet been employed as a conceptual domain model.

Besides structuring the representation of domain knowledge, the semantics of interface information has to be defined. The OOWM up to now offers proprietary web-service interfaces which e.g. allow to query for instances or retrieve the XML-based data model. For integrating additional sensing systems, no interface semantics exist. In consequence, this integration requires manual configuration effort and the transformation of observation data.

A recent approach to the problem of integrating observations from heterogeneous sensor systems (employed e.g. by [9]) is given by the OGC Sensor Web Enablement (*SWE*) initiative [10]. In this approach, a conceptual UML data model is specified, which allows sensor systems on the one hand to publish their capabilities (e.g., which qualities can be measured) and on the other hand to present their measurements according to a standardized description [11]. The SWE approach is a significant step towards promoting interoperability. Yet, when regarded as formal conceptual model for describing observations, the approach shows inconsistencies and lacks the required precision for semantic interoperability [12]. Furthermore, it relies on an externally defined ontology to describe a domain.

In order to promote semantic interoperability for the OOWM, a meta structure for domain modeling as well as a

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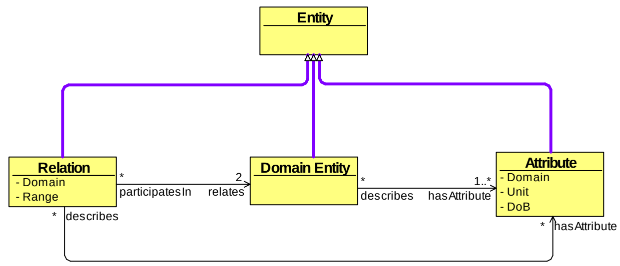

Figure 2. Conceptual view on the OOWM meta model, defining how real-world entities are represented as concepts in background knowledge. The concept Domain Entity models the common features of entities of interest.

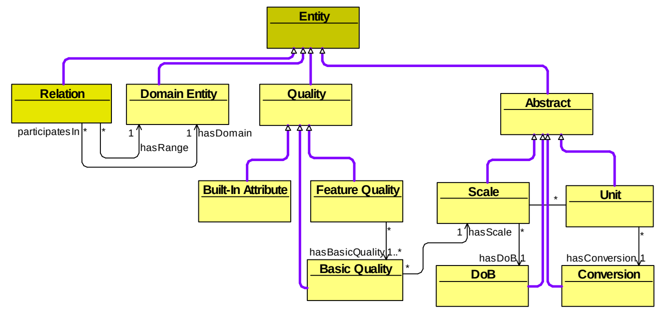

Figure 3. Basic concepts of the OOWM meta model refined as ontology. Attributes are represented by the categories of Quality, constituting attribute domains, and Abstract, defining the features needed to describe attributes.

conceptual model for interface information is needed. This can be achieved by employing an ontology as an integrated approach. To facilitate the use of ontologies as semantic background knowledge for domain modeling as well as to describe interface information objects, we propose to define and employ a meta model for knowledge representation within OOWM. In [13], we took a first step into this direction by presenting an abstract meta model for object-oriented domain modeling, developed with respect to enable extension to existing domain models. In this contribution, we propose a formal representation based on description logic, implementing the model as an OWL DL [14] ontology. This approach allows us to make use of well-supported ontology reasoning technologies for tasks like querying or consistency checking. Furthermore, it allows to share the meta model ontology, e.g. allowing a sensor system not only to provide its observations as an ontology instance, but to perform remote consistency checks prior to transmitting its data. Similar rationales and approaches are followed in [12], [15], where ontologies are used to represent the fundamental terms of OGC observations [11] or pervasive computing context.

Figure 2 displays the conceptual view on the OOWM meta model. In OOWM Background Knowledge, basically an entity-relationship [16] approach is used to model entities occurring in a domain of interest. The most important entities concerned in domain modeling are entities like objects, persons, events or abstractions of these, which are subsumed in the category of Domain Entity. A Domain Entity is characterized by Attributes which describe its qualities, given as the domain of an Attribute, and their quantitative characteristics, given as a probability distribution representing the Degree-of-Belief (DoB) in these values, and, if needed, a unit of measurement. Furthermore, relations can be used to describe the relationships that possible exist between entities in the application domain. A Relation is characterized by a domain and a range of entities on which this relation can be applied. The conceptual view in Figure 2 constitutes an adapted UML specification of the meta model presented in [13]. As a next step, the meta model, and thus the ontology, has to be further refined.

IV. Ontology-based Background Knowledge

In structured approaches to ontology design like [17] an important step is to determine the intended scope of the ontology. This includes the domain, uses and level of abstraction the ontology is intended for. For the OOWM meta model, the scope is to define a semantic meta structure for background knowledge, in which entities from different domains of interest as well as their observations can be described according to the principles of the OOWM approach. This structure is aimed at supporting a semantic access to the observation information stored in the OOWM. It shall support different domains of interest, ranging from large-scale surveillance applications to indoor robotic scenarios. As one ontological commitment, a descriptive approach is chosen, describing real-world entities on a level of abstraction corresponding to human environment perception. Furthermore, a presentism and actualism approach is taken, making the intended knowledge structure time-independent and free of modality, since the concepts of time and probability will have to be represented within the model itself.

For general knowledge to be structured within an ontology, it is recommended to commit to the basic categories of an existing upper level ontology. For the OOWM meta model, the descriptive foundational ontology DOLCE [18] was chosen. In DOLCE, a top-level category named particulars is subdivided into the categories of endurants (entities which are present in their whole at any time and can truly change with time), perdurants (entities existing only in time), qualities (entities that can be observed) and abstracts (entities without spatial or temporal qualities). This high level categorization is adopted to structure the OOWM meta model refinement, as depicted in Figure 3. Besides Relation the concepts of Domain Entity, Quality and Abstract are defined. Domain Entity constitutes the union of all the DOLCE endurants and perdurants which represent the entities being subject to domain modeling. Though not depicted in Figure 3, the categories of Endurant and Perdurant are defined as subcategories of Entity. A Quality describes measurable entities and is further subdivided into a Basic Quality, which constitutes a one-dimensional measurand (like a length, an

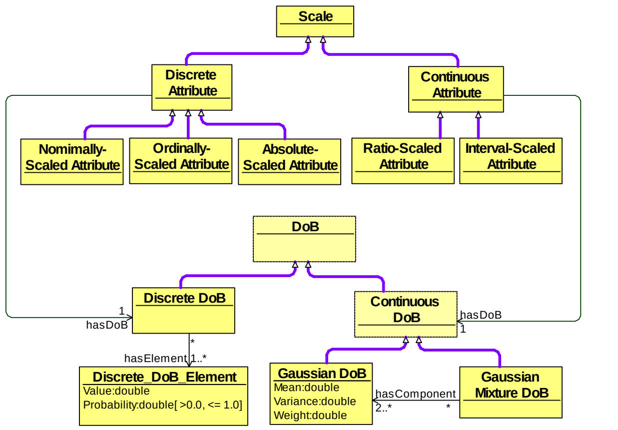

Figure 4. Implementation of attributes in the refined OOWM meta model. Each attribute has a Scale, (e.g., a nominal, ordinal or cardinal scale) and each Scale is associated with a DoB distribution.

angle, etc.), and a Feature Quality, which is build using Basic Qualities (like a position or bounding box). Abstract entities are used to characterize the features of attributes like their Scale, DoB distributions and Unit.

Due to the dedication to DOLCE categories, Attributes in the refined meta model are represented by using the concept of Quality in conjunction with the concept of Abstract. A probabilistic OOWM attribute is thus represented as semantic net in the model. Qualities constitute the possible domains of attributes. Basic Qualities need to specify a Scale. The Scale concept defines subconcepts for the different types of measurement scales, i.e., nominal, ordinal, and cardinal scales. Each Scale is associated with a DoB distribution. As subconcepts of DoB, discrete distributions (specifying a list of value-probability pairs), normal distributions (represented by a mean value and a variance) and sums of normal distributions are modeled. For cardinally scaled attributes, a Unit of measurement has to be specified. The OOWM meta model for example specifies different units of measurement for describing a length, an angle or a velocity. Each Unit of measurement is associated with a Conversion that characterizes how different units can be converted (e.g., by scaling or shifting). For associating Qualities and a respective Unit, SWRL [19] rules can be employed. Figure 4 illustrates the modeling of attributes in the OOWM meta model. Besides using probabilistic attributes, a Built-In Attribute concept needs to be defined for specifying deterministic values, e.g. for the handling of time.

For representing interface information like observation results and structuring background knowledge, the concept of Endurant has to be further refined. This subdivision is illustrated in Figure 5, where categories taken from DOLCE are depicted in gray. Physical Endurant forms the basis for modeling physical entities in the domain of interest. The most important subconcept is Physical Object, which models all entities that exist in space as an entire object. Physical

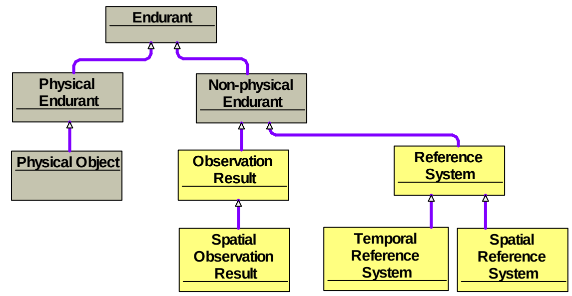

Figure 5. The structure of Endurants as used by the OOWM meta model, with gray boxes representing DOLCE categories. Observations are modeled as the result of an observation process.

Objects are constituents to the union concept Domain Entity. The other important contribution to this union concept is made by temporal entities (which are subconcepts of Perdurant) like Events or Processes.

As Non-Physical Endurant, the OOWM meta model defines the concepts of Observation Result and Reference System. Observation Result constitutes the most important concept for data input to the OOWM. Contrary to [11], [12], observations are not considered as a process, but as a piece of information representing its results. Thus, the concept of Observation Results is modeled as Endurant. A Spatial Observation Result represents an observation containing a spatial reference. Figure 6 depicts the definition of observation results. For defining spatial and temporal references, the meta model defines the concept of Reference System.

For stochastic information processing as employed in the OOWM, observations as well as entity representations have to be assigned with a tangible time reference. Due to this, the OOWM meta model has to define time entities and a temporal reference system. The handling of time in the OOMW meta model is based on the two notions of time instant and time interval, as used for example in OWL-Time [20] and ISO 19108 [21] (here the notion period is used instead of interval). As time instant, the OOWM meta model defines the concept of Point of Time. Points of time are described by a Temporal Position, i.e., a temporal distance to a reference point of time. As mentioned earlier, Temporal Attributes like Temporal Positions constitute Built-In Attributes which are not modeled to be probabilistic but deterministic. Subconcepts of Temporal Position are thus directly represented by standard data types. The details of time representation within the OOWM meta model are depicted in Figure 7. As standard Temporal Reference System, a Gregorian calendar with a ISO 8601 dateTime [22] as Temporal Position description is employed. If needed, the meta model can be extended (in analogy to [21]) by specifying an additional Temporal Reference System, which has to define a temporal reference point, denoting its beginning, as a Gregorian DateTime. Discrete Relative Time is an example of such a Temporal Reference System.

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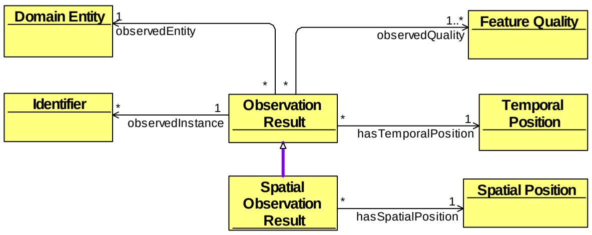

Figure 6. Definition of the concept Observation Result, which models the result of an observation process as information object. It specifies the Domain Entity and Quality observed as well as the observation time.

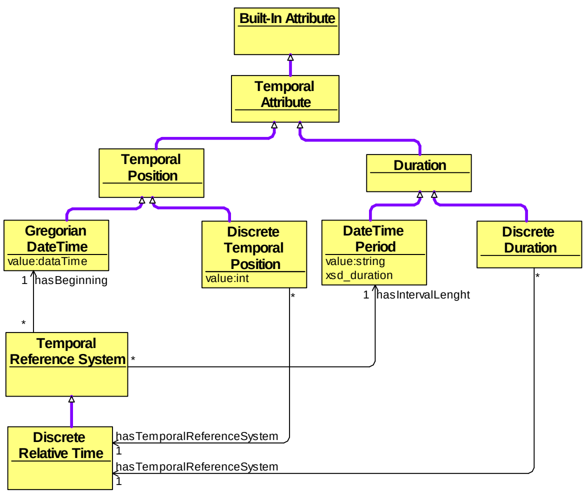

Figure 7. Handling of time in the OOWM meta model. As Temporal Attributes, the concepts Temporal Position and Duration are defined. The concept Temporal Reference System allows extensions to these concepts.

The handling of geospatial information in the meta model concerns qualities like positions, locations and extends. A Spatial Position, being a Quality associated to a Physical Object, is specified using the known World Geodetic System 84 (WGS84) in the meta model. Similar to the handling of time, it is possible to add a Spatial Reference System defining additional Spatial Positions, for example a local Cartesian coordinate system.

V. Web-Based Information Access Interfaces

As described in Section III the OOWM currently does not provide semantic access interfaces for inserting and retrieving OOWM information. To overcome these limitations we propose the use of standardized web-service interfaces and a model-based approach, relying on the proposed ontology, for generating these interfaces. As the OOWM mainly represents geographic information, the proposed interfaces are based upon the well-standardized and widely accepted OGC standards Web Feature Service (*WFS*) [6] and Sensor Observation Service (*SOS*) [7], and the currently discussed OGC standard Sensor Event Service (*SES*) [23].

Figure 8 depicts the current OOWM architecture (see [24]) with the proposed service-oriented extensions. In the

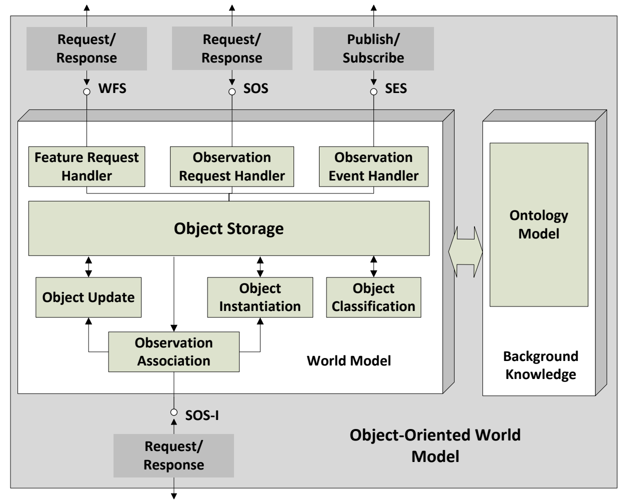

Figure 8. Service-oriented interface definitions. The OGC standard WFS, SOS and SES are employed for accessing OOWM information.

context of the OOWM, the SOS can be used for retrieving information concerning specific entity attributes according to a request/response protocol initiated by a client application like a high level processing module. In case an application wants to get actively informed about new OOWM information, the SES provides an event notification to previously subscribed consumers (push mode). Additionally, the WFS provides a request/response interface for the OOWM that can be used to retrieve aggregated, object-based entity information, which are to be represented as OGC features [25]. As a fourth OGC compliant interface an advanced SOS (SOS-I; I = Insert) [7] interface is available to allow insertion of observations supplied by sensing systems.

Besides the proposed interfaces the extension includes the depicted components Feature Request Handler, Observation Request Handler and Observation Event Handler. These handlers process incoming OGC compliant service requests and respond with adequate OGC compliant service results. The handlers operate on the Object Storage of the World Model and make use of the Ontology Model stored in Background Knowledge. This Ontology Model constitutes a domain-specific extension of the OOWM meta model ontology, thus describing interface objects as well as domain entities. Figure 9 depicts an exemplary domain-specific ontology as extension to the OOWM meta model. The taxonomy of domain entities is to be used in the WFS, SOS and SES for querying object information and in the SOS-I for inserting new observation data to the OOWM.

The SOS-I in conjunction with the Ontology Model can be used to facilitate the semantic integration of additional sensing systems into the OOWM. When using the SOS-I to provide observations to the OOWM, each sensing system will have to describe its observations as an information object which allows to instantiate an Observation Result

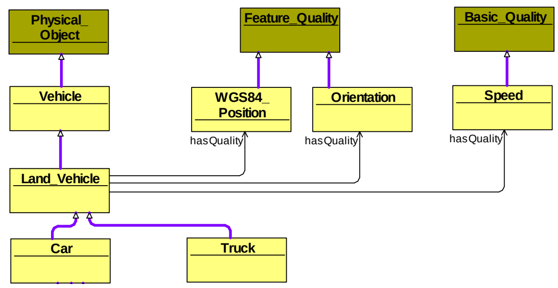

Figure 9. Exemplary domain model based on the OOWM meta model. The taxonomy of concepts is used for queries in the WFS and SOS.

concept in the OOWM. Thus, each SOS-I message must at least specify

- a feature of interest describing either a Domain Entity concept (e.g., Vehicle) or a reference to an known Domain Entity instance (then acting as Identifier),
- an observed property describing the Feature Quality which was observed,
- a measurement value specified as DoB in a unit of measurement corresponding to the observed quality,
- and a time stamp representing the Temporal Position.

Additionally, a Spatial Position can be specified. An example of an XML encoded SOS-I message is given in Listing 1.

```
<sos:InsertObservation service="SOS" version="2.0.0">
 <sos:observation> [...]
  <om:name xlink:href=".../BkOnto.owl#WGS84_Position"/>
  <om:value> <gml:Point gml:id="Spatial_Position">
    <gml:pos srsName=".../EPSG/0/4326">54.9 10.5</gml:pos>
  </gml:Point> </om:value> [...]
  <om:phenomenonTime>
   <gml:TimeInstant gml:id="Temporal_Position">
    <gml:timePosition>2012-09-25T13:01:00.7Z</
         gml:timePosition>
  </gml:TimeInstant></om:phenomenonTime>
  <om:observedProperty xlink:href=".../BkOnto.owl#Speed"/>
  <om:featureOfInterest xlink:href=".../BkOnto.owl#
       Land_Vehicle"/>
   <om:result> [...]
    <swe:elementType name="Speed_GaussianDoB"> [...]
     <swe:field name="GaussianDoB_Mean">
      <swe:Quantity definition=".../BkOnto.owl#Mean">
       <swe:uom code=".../BkOnto.owl#milesperhour"/>
      </swe:Quantity> </swe:field>
     <swe:field name="GaussianDoB_Variance">
      <swe:Quantity definition=".../BkOnto.owl#Variance">
       <swe:uom code=".../BkOnto.owl#milesperhour"/>
      </swe:Quantity> </swe:field> [...]
    </swe:elementType>
    <swe:encoding>
     <swe:TextBlock decimalSeparator="." tokenSeparator=",
          " blockSeparator="@@"/>
    </swe:encoding>
    <swe:values>45,2.5@@</swe:values>
  [...]
</sos:InsertObservation>
```

Listing 1. Excerpt of an XML encoded SOS-I message providing observation information about the velocity of a land vehicle.

For the WFS, the structure of a result message is defined by the queried feature, which in the OOWM corresponds to the queried Domain Entity. When querying for entity information via the WFS, the concept taxonomy will be searched, acquiring and returning all instances of subconcepts for the queried concept, described as instance of the queried concept (according to a cast to a superclass).

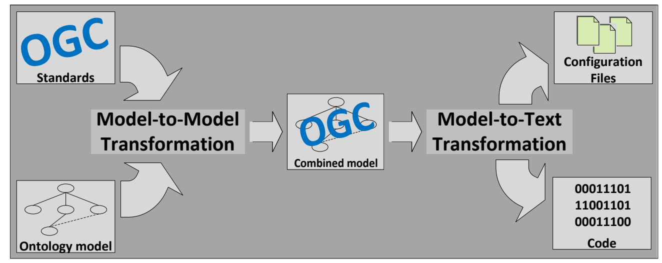

Figure 10. Model transformation process employed in a model-driven approach for generating application code for SOS-I clients in the OOWM.

To ensure for client applications to comply to OGC standards as well as to the OOWM conceptual domain model, methods of model-driven software development (e.g., [26]) can be applied for generating parts of a client implementation, based upon the presented OGC-based interface standards and the OOWM Ontology Model. An automated model transformation process for this purpose is depicted in Figure 10. It can be based upon existing modeling tools like the Eclipse Modeling Project [27]. As initial parts, relevant OGC standards and the Ontology Model form the input to the transformation process. The first step of the process is a model-to-model transformation weaving OGC interface definitions and ontology to one combined model that includes both source models. The second step is a model-to-text transformation of the combined model, resulting in platform specific code and configuration files.

As advantages of this model-driven approach, client applications can be provided with an integrated data model. This data model can address syntactic and semantic aspects of information exchange with the OOWM by providing common data structures as well as formalizing their conceptual meaning. In addition, remote consistency checks on observation data can be performed prior to transmitting it to the OOWM via SOS-I, for ensuring model-compliant data. An issue to be solved within this approach is to define a way for receiving the ontology model via OGC web-services in a standard-conform manner.

VI. Conclusion

For promoting semantic interoperability in Object-Oriented World Modeling, an ontology-based meta model for structuring domain knowledge and interface information objects has been presented. This meta model facilitates the integration of additional sensing systems into the OOWM and enables information exchange on a semantic level. Furthermore, it can serve as an overarching ontology for various domain models when employing the OOWM in different application domains. When implemented as a formal ontology, reasoning and consistency checks can be performed by available tools, thus allowing sensing systems to perform such checks prior to transmitting their observations. Furthermore, semantic interface descriptions for a web-service access to OOWM information based on standards like OGC WFS and SOS have been proposed on the basis of the meta model.

Beside promoting interoperability, the proposed meta model ontology can be used as structure for semantically extending an existing background knowledge by concept learning approaches. In addition to formal knowledge sharing as enabled by ontologies, it is even possible to perform a kind of distributed concept learning in this way.

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