A Pattern-based Framework for Representation of Uncertainty in Ontologies

Miroslav Vacura[1], Vojtěch Svátek[1], and Pavel Smrž[2]

[1] University of Economics, Prague
W. Churchill Sq.4, 130 67 Prague 3, Czech Republic
vacuram|svatek@vse.cz
[2] Brno University of Technology
Božetěchova 2, 612 66 Brno, Czech Republic
smrz@fit.vutbr.cz

Abstract. We present a novel approach to representing uncertain information in ontologies based on design patterns. We provide a brief description of our approach, present its use in case of fuzzy information and probabilistic information, and describe the possibility to model multiple types of uncertainty in a single ontology. We also shortly present an appropriate fuzzy reasoning tool and define a complex ontology architecture for well-founded handling of uncertain information.

1 Introduction

Currently available Semantic Web technology still provides inadequate foundations to handling uncertainty. One of main achievements of the Semantic Web initiative was the development of standardization of common web ontology language – OWL. While OWL datatypes provide means for including numeric uncertainty measures and necessary structural foundations ad hoc, there is no standardized way of representing uncertainty. There is a widespread opinion that for adequate representation of uncertainty in OWL some language extension is necessary, be it at the level of language syntax or of higher-level patterns.

An example of the first is Fuzzy RDF [11], which extends RDF from triple to couple (value, triple), adding to the triple a "value". In contrast, Fuzzy OWL [14] is based on fuzzy description logics; a simple extension to OWL syntax has already been proposed to represent it [13]. There are also approaches based on modeling probability. BayesOWL [17] extends OWL using Bayesian networks as the underlying reasoning mechanism and probabilistic model. PR-OWL [3] is based on MEBN Theory (Multi-Entity Bayesian Network).

Probability theory is also foundation of recently introduced probability description logics P-$\mathcal{SHIF}$(D) and P-$\mathcal{SHOIN}$(D) [9]. In this case probabilistic knowledge base consists of a PTBox (classical DL knowledge base along with probabilistic terminological knowledge) and a collection of PABoxes (encoding probabilistic assertional knowledge about a certain set of individuals). However no formal way of RDF/XML encoding is provided. This probabilistic description logics theory is basis of Pronto,[3] probabilistic extension for Pellet DL reasoner. Pronto uses OWL 1.1's annotation properties for encoding probability information in OWL RDF/XML. Drawback is that the formal semantics of annotation properties is limited.

There is also an approach based on using ontology patterns to define n-ary relations described in "Best Practices" W3C document [5] that can be applied to uncertainty and in principle consists of creating ad hoc properties and classes for every ontology and every type of uncertain information described by ontology. This however results in inability to use any generic uncertainty reasoner: if one needs to introduce uncertainty handling to an existing ontology, it is necessary to do re-engineering of such ontology (removing classes and properties and creating new ones), which renders the new ontology incompatible with the original one. We will show that our approach is superior to "Best Practices" approach in most cases as it does not have such drawbacks. Our approach also provides common OWL syntax for various kinds of uncertainty (like fuzziness or probability) without the need to extend the OWL standard.

2 Pattern-based representation of fuzziness

This section will describe representing fuzzy information based on Fuzzy OWL semantics [14] using our uncertainty modeling pattern. Although fuzziness isn't, exactly said, type of uncertainty, we will show that our approach is usable to represent fuzzy information. In this example we will consider representing fuzzy information in the form of facts, i.e. A-Box from description logic (DL) point of view.

The key principle of our approach to representing fuzzy information is the *separation* of crisp ontology from fuzzy information ontology. While an ontology can be build from scratch using our pattern-based approach, it is also possible to extend an existing crisp ontology (base ontology) to represent fuzzy information by creating an add-on ontology (fuzzy ontology) that only contains fuzzy information. Separation of uncertainty related information from crisp information can be in practice realized by storing these sets of RDF triplets in different RDF repositories. Therefore performance of data querying etc. when not using uncertainty related information is not affected. This also allows simple way of data distribution among multiple servers with RDF repositories. Such separation is not possible using "Best Practices" approach [5] or if we use annotation properties for encoding uncertainty information.

We allow the fuzzy ontology to be OWL Full, which may be at first sight surprising. Most ontology applications that use some kind of reasoning presuppose OWL DL compliant ontology for the sake of decidability and availability of reasoning tools. In our case we only suppose that the base ontology is OWL DL compliant. The base ontology can be used separately from the fuzzy ontology, and regular OWL DL crisp reasoning tools can be applied to it. There

[3] `http://pellet.owldl.com/pronto`

is no reason to apply crisp reasoning tools on the fuzzy ontology since it only includes information regarding uncertainty (although it be used for pruning the base ontology before crisp reasoning, i.e. filtering out relationships with fuzzy value under some threshold). When the user has a tool that supports fuzzy reasoning, we suppose that it either accepts our pattern-based syntax or it has some other proprietary syntax format and we need to convert the base and fuzzy ontology together to this format before reasoning. In either case a fuzzy ontology conforming to OWL Full standard is not a problem.

2.1 Fuzziness in instantiation axioms

Instantiation axioms are assertions of form $\langle a : C \bowtie n \rangle$ – facts saying that individual a belongs to class C, n is level of certainty $(0, 1)$ and $\bowtie$ is one of $\{\leq, <, \geq, >\}$. As an example we can take a metro surveillance application which should, based on multimedia information (cameras, microphones), decide whether a person is classified as 'problem person'. In such a case we have an axiom saying that an instance person-1 belongs to class problem-person with some level of uncertainty. We introduce a few constructs that enable us to model such axioms with uncertainty by ontology patterns. For each crisp axiom of base ontology we create a new individual belonging to class fuzzy-instantiation, which will have several properties attaching it to that crisp axiom in base ontology and implementing uncertainty. Properties fi-instance and fi-class characterize the membership of an individual person-1 to class problem-person. Property f-type defines the type of uncertainty relation ($\bowtie$) and datatype property f-value defines the level of uncertainty n. The complete pattern is depicted on Fig. 1 (individuals are grayed and classes are bright).

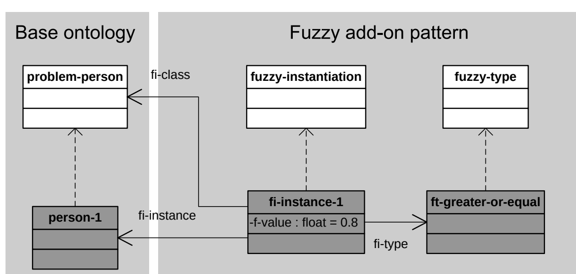

Fig. 1. Instantiation pattern

The following OWL code is part of the base ontology that describes individual person-1 as belonging to class problem-person. This is part of standard crisp OWL DL ontology and is unmodified by adding uncertainty information.

```
<rdf:Description rdf:about="#person-1">
  <rdf:type rdf:resource="#problem-person"/>
```

```
</rdf:Description>
<rdf:Description rdf:about="#problem-person">
  <rdf:type rdf:resource="http://www.w3.org/2002/
  07/owl#Class"/>
</rdf:Description>
```

The next example is part of OWL code of fuzzy add-on ontology that is separated from the base ontology and contains fuzzy information. This part shows fi-instance-1 – an individual that is used to describe fuzzy information regarding the instantiation axiom presented in the previous OWL code example. It says that the individual person-1 belongs to class problem-person with certainty level greater or equal to 0.8.

```
<rdf:Description rdf:about="#fi-instance-1">
  <f-value rdf:datatype="http://www.w3.org/2001/
   XMLSchema#float">0.8</f-value>
  <fi-class rdf:resource="#problem-person"/>
  <fi-type rdf:resource="#ft-greater-or-equal"/>
  <rdf:type rdf:resource="#fuzzy-instantiation"/>
  <fi-instance rdf:resource="#person-1"/>
</rdf:Description>
```

2.2 Uncertainty in role axioms

Role axioms are assertions of form $\langle(a, b) : R \bowtie n\rangle$ – facts saying that individual a and individual b are in relation R, level of certainty is n and $\bowtie$ is one of $\{\leq, <, \geq, >\}$. The complete pattern is depicted on Fig. 2. OWL code of role axioms is analogous to OWL code of instantiation axioms.

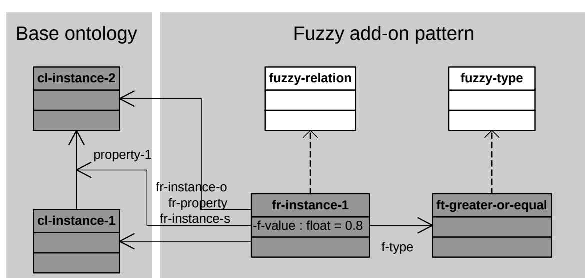

Fig. 2. Relation pattern

The following OWL code is part of standard role axiom definition with regards to instances cl-instance-1, cl-instance-2 and property property-1. It is again OWL DL compliant.

```
<class-1 rdf:ID="cl-instance-1">
        <property-1 rdf:resource="#cl-instance-2"/>
</class-1>
<class-1 rdf:ID="cl-instance-2"/>
<owl:Class rdf:ID="class-1"/>
<owl:ObjectProperty rdf:ID="property-1"/>
```

Next OWL code is part of fuzzy add-on ontology that refers to the previous relation and adds fuzzy information to it.

```
<rdf:Description rdf:about="#fr-instance-1">
  <rdf:type rdf:resource="#fuzzy-relation"/>
  <f-type rdf:resource="#ft-greater-or-equal"/>
  <f-value rdf:datatype="http://www.w3.org/2001/
                         XMLSchema#float">0.8</f-value>
  <fr-instance-o rdf:resource="#cl-instance-2"/>
  <fr-instance-s rdf:resource="#cl-instance-1"/>
  <fr-property rdf:resource="#property-1"/>
</rdf:Description>
```

We use the property fr-instance-o to define object individual, fr-instance-s to define subject individual, fr-property to define to which property we assign fuzzy value (there can be more than one relation between same two individuals). We also use f-type property to define type of relation ($\bowtie$) and again datatype property f-value that defines the level of uncertainty n.

3 Universal uncertainty modeling

As we have already stated one of major advantages of our modeling approach is that it enables us to model various kinds of uncertainty. This is not limited to modeling different kind of uncertainty in each case but using our method one can include various kinds of uncertain information in same ontology at the same time. Our method is also not limited to kinds of uncertainty presented in this paper but represents core of more general framework for handling uncertain information in ontologies, which is strictly modular and easily extensible. Illustration of handling multiple types of uncertainty is depicted in Fig. 3.

In real world applications not only modeling but also reasoning on top of ontologies is necessary. This is why we focus to implementation of our pattern-based representation to available reasoning engines. In context of EU funded project K-Space[4] we are implementing presented fuzzy modeling syntax to FiRE reasoning engine. [5]

[4] http://www.k-space.eu
[5] http://www.image.ece.ntua.gr/∼nsimou

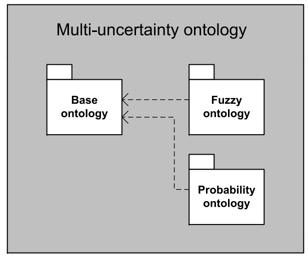

Fig. 3. Handling multiple types of uncertainty in same ontology.

4 Architecture supporting reasoning with uncertainty

Using components described above we can define well-founded architecture of ontology that fully supports handling uncertainty on basis of Uncertainty Modeling Framework. Such architecture is based on standard concept of well-founded ontology: crisp ontology is aligned to foundational ontology (in case of CARE-TAKER example it is DOLCE [10]) while fuzzy and probabilistic ontologies are based on appropriate patterns of Uncertainty Modeling Framework. Such architecture is modularized, so these parts of ontology are separated to independent modules. On top of these ontologies there can be number of different specialized reasoners operating. Complete architecture is on Fig. 4.

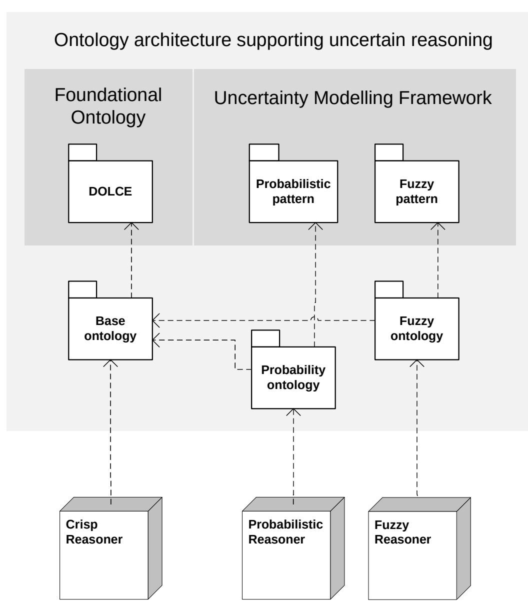

Fig. 4. Ontology architecture supporting reasoning with uncertainty.

Question may be asked why to use fuzziness and probability in the same time. We don't propose such use, however, we enable user to include different types of uncertainty in single ontology if he for whatever reason chooses to.

5 Conclusions and future work

Our approach to representing uncertainty in ontologies has the following useful features: it can use existing crisp ontologies without the need to re-engineer them; it is 'backward compatible' with crisp DL reasoning tools and other software; it uses strictly standard OWL language with no extensions; it can be used to represent different kinds of uncertainty (like probability and fuzziness) in the same ontology; it separates data regarding uncertainty from base data.

As uncommon feature may be seen that our fuzzy add-on is OWL Full and not OWL DL, but we have argued in previous sections, that due strict separation of fuzzy ontology from base ontology this does not imply problem in real world applications.

In future we plan to extend coverage of Uncertainty Modeling Framework and to provide support and integration to other reasoning tools that can reason over uncertain information.

As one of motivations for our research we see the CARETAKER project,[6] which comprises advanced approaches to recognition of multimedia data. More precisely, CARETAKER will focus on the extraction of structured knowledge from large multimedia collections recorded over networks of cameras and microphones deployed in real sites. The produced audio-visual streams, in addition to surveillance and safety issues, could represent a useful source of information if stored and automatically analyzed.

6 Acknowledgments

Miroslav Vacura, Vojtěch Svátek are supported by the EC under FP6, project Knowledge Space of semantic inference for automatic annotation and retrieval of multimedia content – K-Space (no.: FP6-027026), and first one also by the Czech FIGA NF VSE grant. Pavel Smrz is supported by the EU FP7 project KiWi (ref. no.: 211932).

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[6] `http://www.ist-caretaker.org/`

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