METRIC TEMPORAL LOGICS FOR EVOLVING ONTOLOGY ANALYSIS

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Ontology building has drawn huge attention since early nineties of the XXth century as one of the approaches to semiotic modeling of a domain [1].

According to Guarino [2] "ontology is a logical theory accounting for the intended meaning of a formal vocabulary".

Ontologies are widely used in different fields[1]: in scientific research in physics, biology, medicine; in business and industry; for intelligent information retrieval in local/global information systems, including WWW; in education; in natural language processing; for data/knowledge integration from distributed heterogeneous sources.

Dynamic nature, ability to evolution is an inevitable feature of an arbitrary domain. Successful solutions of ontology-based data/knowledge integration, intelligent information retrieval from distributed sources are to take into account evolution of ontologies describing the knowledge of the information sources.

Ontology versioning and change detection are one of the research challenges [4] for the Semantic Web. Recent works on ontology versioning pay special attention to ontology evolution logical analysis.

Approaches to ontology changes detection and storage basically work on syntactic layer (see e.g.[5]), they are bounded to particular ontology definition language, and provide sets of heuristics/rules for change detection. Common drawbacks of this class of the approaches are discussed in [6]: several changes may influence (or even discard) one another and heuristics/rules may fail in detecting complex changes.

Proof-theoretic approach to ontology evolution analysis, first introduced in MORE [7], overcomes the drawbacks of other approaches. First of all, it is ontology language-independent: high-level language LTLm was introduced for changes analysis. Secondly, reasoning over ontology changes instead of querying changes was proposed, which allowed to rely not only on heuristics/rules of change detection, but to deduce complex changes. Finally, LTLm is based on temporal logic, which is natural as far as changes are characterized with time moments, when they occur.

However, analysis of [7] has shown that the proposed temporal logic LTLm has its own drawbacks: it is impossible to define the distance between time points when changes occur, it is impossible to make complex queries binding both future and past moments, it is impossible to obtain the time point, when a particular change occur etc. Finally, the logical properties of LTLm were not investigated, and its computational complexity was not analyzed.

Presented research aims at the development of temporal logics which will be free of the mentioned drawbacks. The paper provides comprehensive analysis of the proposed temporal logics.

The basic temporal calculus constructed for reasoning over ontology changes is *propositional metric temporal calculus PTC*(*MT*), based on the propositional metric temporal language *LMP*, first introduced by A.Prior [8]. This language extends propositional symbols and connectives with two temporal modalities *Fn* ("it will be in *n* time points") and *Pn* ("it was *n* time points before").

Definition 1. **The alphabet of *PTC*(*MT*)**.

Let $PROP = \{p, q, p', q', ...\}$ be propositional symbols, $NUM = \{n, m, k, ...\}$ be a set of natural numbers and number "zero", $N \cup \{0\}$, $NUMVAR = \{i, j, k, ...\}$ be a set of numerical variables, $NUM \cup NUMVAR = \{x, x_1, x_2, ...\}$ be a set of names, defining numerical variables and the elements of *NUM*, $PRED = \{\Pr^s, s = 1,2,...\}$ be a set of *s*-ary predicate symbols, defined over $N \cup \{0\}$,

[1] For more comprehensive review please see [3].

$MOD = \{Fx, Px, x \in NUM \cup NUMVAR\}$ be a set of modalities. Then well-formed formulae set *WFF* on symbols from *PROP*, *NUM*, *NUMVAR*, *PRED* and *MOD* consists of the following formulae:

$$WFF := p | \neg\varphi | \varphi \wedge \psi | \varphi \vee \psi | \varphi \supset \psi | \Pr^s(x_1,..., x_s) | Fx\varphi | Px\varphi | \exists i\varphi | \forall i\varphi ,$$

for each $\varphi \in WFF$.

Axioms and the deduction rules for *PTC*(*MT*) are combined of propositional axioms/deduction rules and temporal axioms/deduction rules, defining time to be unbounded linear and discrete.

Definition 2. **Model of *PTC*(*MT*)**.

PTC(*MT*) is interpreted in Kripke model $M = < W, dist, \{R_F, R_P\}, \xi, \xi^s_{PRED} >$, where W is a non-empty set of possible worlds, $dist : W \times W \to N \cup \{0\}$ is a metric on *W*, R_F, R_P are accessibility relations to the future and to the past, $\xi : PROP \to 2^W$ is an interpretation function, assigning each propositional symbol its truth value in each possible world, and $\xi^s_{PRED} : PRED \to 2^{W^s}$ is an interpretation function for predicate symbols.

Constructive proofs of *PTC*(*MT*) soundness, completeness [9] and decidability [10] were obtained with help of metric semantic tableau rules introduced. Computational complexity was shown to be EXPTIME.

PTC(*MT*) allows satisfiability checking for statements about future/past situation at given distances (e.g. $F5\varphi \wedge P2(\neg\psi)$), about possible future/past situation (e.g. $F5\varphi \wedge \exists iPi(\neg\varphi)$), about all possible future/past situations (e.g. $F5\varphi \wedge \forall iPi(\neg\varphi)$).

It is easy to see that indirectly all statements of *PTC*(*MT*) are evaluated against some "current" state, though direct definition of the current state (or *version*, in terms of ontology versioning) is not allowed. This shortcoming may be eliminated with help of *hybridization* of *PTC*(*MT*).

Hybrid logics (see introduction in [11]) form a class of modal logics that allows referring to elements of Kripke models – "possible worlds" – directly in formulae.

Logical languages used for hybrid logic are at least two-sorted: they have a special sort of atomic objects called *nominals*. Each nominal names exactly one possible world of Kripke model.

Definition 3. **The alphabet of *Hybrid PTC*(*MT*), *HPTC*(*MT*)**.

Given an alphabet of *PTC*(*MT*), let $NOM = \{a, b, c,...\}$ be a non-empty set of nominals, $@_a$ – be *satisfaction* operator ("at the world named *a* it is true that…"). Then well-formed formulae set *WFF* on symbols from *NOM*, *PROP*, *NUM*, *NUMVAR*, *PRED*, *MOD* with help of operator $@_a$ consists of the following formulae:

$$WFF := a | p | \neg\varphi | \varphi \wedge \psi | \varphi \vee \psi | \varphi \supset \psi | \Pr^s(x_1,..., x_s) | Fx\varphi | Px\varphi | \exists i\varphi | \forall i\varphi | @_a\varphi ,$$

for each $\varphi \in WFF$.

Axioms and the deduction rules of *HPTC*(*MT*) extend those for *PTC*(*MT*) to incorporate satisfaction operator properties. Model definition for *HPTC*(*MT*) extends the interpretation function to deal with nominals, $\xi : PROP \cup NOM \to 2^W$.

HPTC(*MT*) is sound, complete and decidable [12]. The proofs are also constructive and rely on hybrid tableau rules, adopted for metric temporal logic.

HPTC(*MT*) allows satisfiability checking for all *PTC*(*MT*) statements against given particular state. E.g. it is possible to evaluate $@_a(F5\varphi \wedge \forall iPi(\neg\varphi))$, where "a" – is a name of some ontology version.

The results obtained for propositional metric temporal calculus and its hybrid extension can be embedded into known reasoners for propositional modal logics.

In this respect of great interest is the adaptation of the tableau rules proposed for *PTC*(*MT*) and *HPTC*(*MT*) for reasoning over Description Logics [13] family of ontology languages, widely used in Semantic Web applications.

Presented research introduces decidable description logic *ALCIO*(*MT*) for metric linear unbounded time.

Definition 4. Description Logic *ALCIO*(*MT*).

Let A, B denote atomic non-temporal concepts, R - atomic role, E, F - complex non-temporal concepts, P - complex role, C, D - complex temporal concept, $\{o\}$ - object nominal (denoting an individual is some possible world), $\{a\}$ - temporal nominal (denoting possible world, e.g. ontology version). Then the following rules generate complex concepts/roles:

$$E, F \rightarrow A \mid top \mid bottom \mid E \; intersect \; F \mid E \; union \; F \mid not \; E \mid \exists R.E \mid \forall R.E \mid \{o\}$$

$$P \rightarrow R \mid P^{-1}$$

$$C, D \rightarrow E \mid \{a\} \mid C \; intersect \; D \mid C \; union \; D \mid C@\{a\} \mid Fn \; C \mid Pn \; C \mid$$
$$\mid somefuture \; C \mid somepast \; C \mid allfuture \; C \mid allpast \; C$$

Existential modalities *somefuture* and *somepast* are semantically equivalent to modalities $\exists iFi, \exists iPi$ used in *PTC*(*MT*). Universal modalities *allfuture* and *allpast* are equivalent to modalities $\forall iFi, \forall iPi$ of *PTC*(*MT*).

Definition 5. The model of *ALCIO*(*MT*).

ALCIO(*MT*) is interpreted over Kripke model $M = < \Delta, dist, \{R_F, R_P\}, I >$, where $\Delta = \{\Delta^k\}_{k \in N \cup \{0\}}$ is a set of possible worlds, Δ^k is a set of individuals in *k*-th possible world, $dist: \Delta \times \Delta \rightarrow N \cup \{0\}$ is a metric on Δ, R_F, R_P are accessibility relations, I is an interpretation function.

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