The Meaning and Sources of Dynamics in Domain Ontologies

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Abstract – The generalized approach on ontology dynamics is presented based on similarity/distance measures. Dynamic state is representative description of the temporal properties of the ontology. Opposite properties "static-dynamic", "crisp-fuzzy" are considered as alternative exhibition of ontology in different stages of this life cycle and in different structures. The main sources of dynamics in ontologies are analyzed as well as its relationship with formal ontology presentation. The advantages of proposed generalized approach are discussed in accordance of ontologies creation, development, maintenance in different application area.

Index Terms – dynamic ontology, formal ontology model, fuzzy sets, ontology similarity

I. INTRODUCTION

In the last 15 years ontologies have been established as wide accepted approach for the knowledge structuring, representation, processing, reasoning and reusing [1, 2, 3, 8, 14, 16]. Among numerous definitions of the notion "Ontology" the most usable and relevant to the aims of the present work is Studier statement [1], based on previous Gruber definition [3]: "An ontology is a formal explicit specification of a shared conceptualization". This formulation is adequate for a broad range of domain ontologies as well as it corresponds in a constructive way to different stages of ontologies life cycle. In the presented contribution the main attention is paid to the properties of a one relatively new class of ontologies – "dynamic ontologies" [4, 5, 11, 20, 21]. Dynamic ontologies possess a lot of peculiarities, distinguishing them from the traditional static ontologies. These peculiarities made possible to accept a more general consideration of the ontologies like short time and long time changes, uncertainty, fuzziness, similarity, approximate modeling, representation and reasoning. From one side the dynamic ontologies could be considered as a certain stage of traditional static ontologies during their creation, development and employment. At the same time final form of ontology or at least a part of it could be with dynamic behavior. This will be a result of variety of reasons. The attempt to recognize the origins of dynamics in ontologies is one of the main goals in this work. Dynamics could not be a priori property. It should be recognized via similarity/distance measures formation and calculation. The metrics acceptance in the knowledge space is another emphasis in this contribution. An attention is paid to present the usually accepted "inverse-approximate" as a possible generalized untresholded properties, which could be observed in the certain ontology at the whole or into their particular parts in short or long time prospective.

2. MAIN PROPERTIES OF ONTOLOGIES

A. Formal ontology models (FOM)

A lot of Formal Ontology Models (FOM) have been proposed [1, 2, 9, 14, 15, 16], but a satisfactory general FOM is still not accepted. In our investigation some popular FOMs have been used in dependence on the problems considered.

- A FOM of "light weight" ontology [1, 2]

$$O_L=<X, R, A, I>, \quad (1)$$

X – is a set of concepts in a particular domain,
R – is a set of relations between the concepts,
A – is a set of attributes and properties of the concepts,
I – is a set of interpretation functions of the possible meanings/values of the concepts/attributes.

- A FOM of "heavy weight" ontology [1, 2]

$$O_H=<X, R, A, I, F, W>, \quad (2)$$

where additional according eq. (1) notions are
F – a set of axioms,
W – a set of inference rules.

- Reduced ROM [15]

$$O=<X, R, \Sigma>, \quad (3)$$

where Σ is a finite set of interpretation, constrain and axiomatization functions.

- FOM of ontology system [15]

$$O_S=<O^{meta}, \{ O^{d\&t} \}, W>, \quad (4)$$

where
O^{meta} – ontology of higher hierarchical level,
O^d – is a domain ontology,
O^t – is a task ontology

- FOM of multi-ontologies [2]

$$O_\Sigma=< O_S, R_\Sigma, F_\Sigma, I_\Sigma>, \quad (5)$$

O_S – is a finite set of ontology systems,
R_Σ – is a set of interontolgy relations,
F_Σ – is a set of interontology axioms,
I_Σ – is a set of interontology interpretations.

B. Similarity measures and ontologies mapping

A big number of methods for similarity estimation between ontologies have been developed [1, 2, 8, 9, 10], but generally accepted approach still don't exists. Nevertheless some basic characteristics of the closeness metrics are commonly adopted:

- Normalization in the interval [0, 1].

- Acceptance of real similarity function into the this interval
  $\mathrm{sim}(x, y) : S^2 \quad [0, 1]$
- Reflexity and symmetry of the similarity function
  $\mathrm{sim}(x, y)=1$
  $\mathrm{sim}(x, y)=\mathrm{sim}(y, x) \qquad (6)$
  for $\forall x, y \in S$
- The comparison covers elements from the same kind (concepts, attributes, roles etc.).
- Abstract ROM should be used.
- The distance between ontologies could be used as a measure of similarity.

In the present investigation as a measure for closeness is accepted the distance ρ

$$\rho^2(O_1, O_2) = \frac{1}{2N} \sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij} \{ \Psi_{ij}(X_i, X_j)\big|_{O_1} - \Psi_{ij}(X_i, X_j)\big|_{O_2} \}^2 \qquad (7)$$

where:

X_i are concepts (i,j=1,N); w_{ij} is normalized distance between X_i and X_j; w_{ij} are weight coefficients; O_1, O_2 represent two states of the same ontology in different time intervals or states of two similar ontologies at the same time.

The metrics for similarity/closeness are very important in order to answer a number of questions, currently actual for each ontology:

- Which is definitely the conformity (consensus) area of multiontological systems (5), which make available to be co-operatively used heterogeneous and changeable information?
- Could one recognize such changes in the ontology (1), (2), (3), or ontology system (4), (5), which impose implementation of:
  - Dynamic ontology models,
  - Quasi-dynamic ontology models,
  - Incremental updating of static ontology?
- Is there convincing prerequisites in order to accept fuzziness as an attribute for a given ontology?
- Is there strong similarity measures arguments to refer given ontology towards a certain of the following dynamic classes of ontologies with:
  - Evolving structure,
  - Arising completeness, scope, quantity of concept's attributes and instances,
  - Changing relationships, axioms, interpretations?
- Could be distinguished quantitatively the results received by approximate reasoning from these of fuzzy logic-based estimations on ontologies distance?
- Could metrics methods be a constructive basis for a development of certain new approaches for design and improvement of ontologies namely:
  - Ontology factorization on consensual and nonconsensual parts,
  - Isolation of dynamic and static parts in given changeable ontology,
  - Creation of evolving ontologies,
  - Ontology development – enrichment, refinement, redundancy rejection, merging,

    - Ontology simplification – forming layers with a different level of abstraction; elimination of branches with rare visits; removing close classes, subclasses, attributes, relations?
- Design of Truth Maintenance System (TMS) [1, 2].

C. Ontology life cycle

Each ontology could be considered as certain changeable entity, which passes all stages of its own *life cycle*, as it is shown in Fig. 1. Final running state of the ontology could be static one, but intermediate stages obligatory will consider dynamic elements.

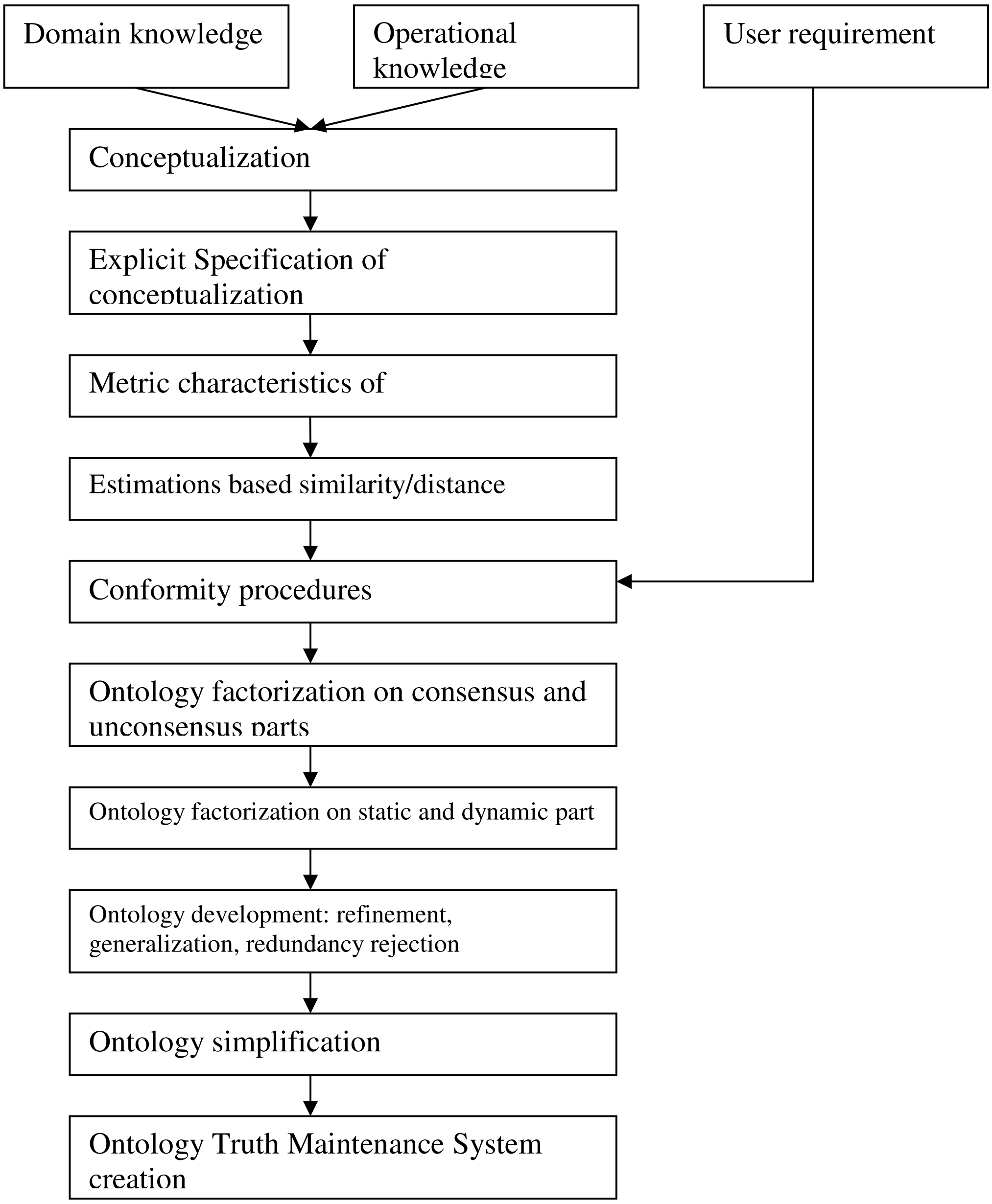

Fig. 1. Ontology life cycle.

The development stage of dynamic ontologies is more sophisticated than in case of the finally static ontologies. They will be considered bellow in details.

D. Ontology state

Definition 1: Ontology state S represents cumulative set of all possible combinations of the formal ontological model (FOM) at given instant. Thus for the heavy weight ontology could be written:

$$O(S(k))=\langle X(k), R(k), A(k), I(k), F(k), W(k)\rangle, \quad (8)$$

where k is discrete time.

Definition 2: In a case of composite ontology or ontology system (4) the common state represent a vector containing the partial ontology's states:

$$S(k)=(S_1(k), S_2(k),\ldots, S_n(k)) \quad (9)$$

Definition 3: Each state $S_i(k)$ of i-th partial ontology O_i from eq. (9) represents a vector of the corresponding FOM. For the model (3) could be written:

$$S_i(k)=(S_{iX}(k), S_{iR}(k),\ldots, S_{i\Sigma}(k)) \quad (10)$$

Ontology state in general case could possess a number of dimensions:

- Temporal $S=S(k)$, where k is discrete time.
- Spatial $S=S(z)$, where z is a space variable.
- Degree of similarity $S=S(\gamma)$, where γ is a degree of similarity.
- Fuzziness $S=S(\mu)$, where μ is a set of membership functions.

Definition 4: A generalized state is determinated as:

$$S_G(k)=(S(k), S(z), S(\gamma), S(\mu)). \quad (11)$$

Since the arguments z, γ and μ could be in dependence on the discrete time k, the generalized state could be represented in the form:

$$S_G=S_G (k, z(k), \gamma(k), \mu(k)). \quad (12)$$

E. Uncertainty and fuzziness of ontologies

Traditionally the ontologies are considered as exact in Boolean sense "Truth-false" [1, 2, 5, 11, 16]. In very limited number of works, based mainly on approximate reasoning [15, 16, 17], this approach is extended including some different kind of ontologies. From the point of view of clarity the ontologies could be classified as follow:

- Approximate ontologies with approximate knowledge presentation and processing, e.g.:

  <A=X with confidence kX> e.g. k=0.9

  <A=X with accuracy kX> e.g. k=0.95

- Fuzzy ontologies with fuzzy presentation of all or only a part of ROM components, e.g.

$$\langle X= \mu(Z)\rangle,\ \mu(Z) \in M(Z),\ |\mu(Z)|\leq 1 \quad (13)$$

Here $\mu(Z)$ is a membership function in a usual sense accepted in the fuzzy logic [18].

III. DYNAMIC ONTOLOGIES

In last few years a new paradigm for "dynamic ontology" gains popularity [4, 5, 6, 11, 20, 21]. Unfortunately the most of works has only conceptual or case-based orientation and treat only some of the dynamical properties and possibilities of the dynamic ontologies. Here an attempt is done to characterize more broadly the dynamic ontologies.

A. The main statements

The dynamic of ontologies will be considered here towards the discrete time, e.g. only on temporal aspect.

Definition: An ontology is dynamic in temporal sense if the next inequality is satisfied

$$\rho\{O(S(k+r)) - O(S(k))\} \geq a \qquad (14)$$

where:

ρ is an accepted similarity (distance) metrics, e.g. according (7),

a is a threshold value, e.g. a=0.1,

S(k), S(k+r) are the ontology states in the inequality (14) is satisfied for first time.

A graphical illustration of dynamic ontology is presented in strongly simplified way in a Fig. 2.

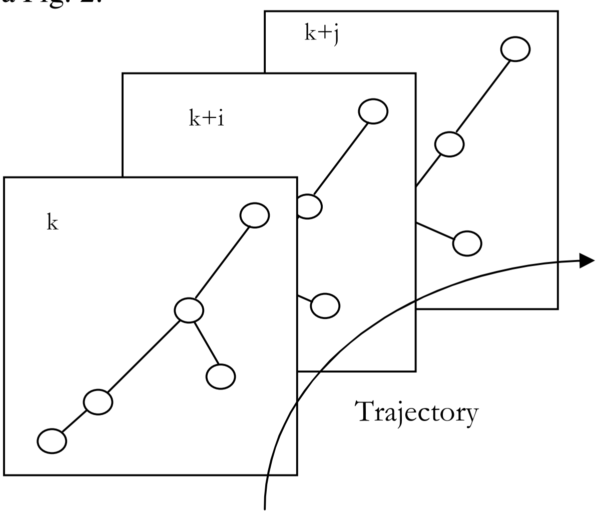

Fig. 2. Scheme of ontology dynamics.

With respect to the factor "time" the ontology could be classified as

- Static ontology, in which all components of the FOM (1)-(5) are time invariant and inequality (14) will not be satisfied for any r.
- Quasi-dynamic ontology, in which incremental updating is necessary for a rare time intervals r, but between these updating the ontology is static one.
- Dynamic ontology, in which inequality (14) is satisfied all the time intervals (e.g. r=1).

In reference to the factor “accuracy of presentation” as mentioned above the dynamic ontologies could be considered as

- Crisp ontologies in which all FOM components are crisp value, notions or relationships.
- Semi-fuzzy ontologies, in which part of the ROM elements are crisp, and the rest are fuzzy.
- Fuzzy ontologies, in which all FOM components are fuzzy.

In a case of fuzzy interpretation the notion “dynamics” could be represented as shown in Fig. 3.

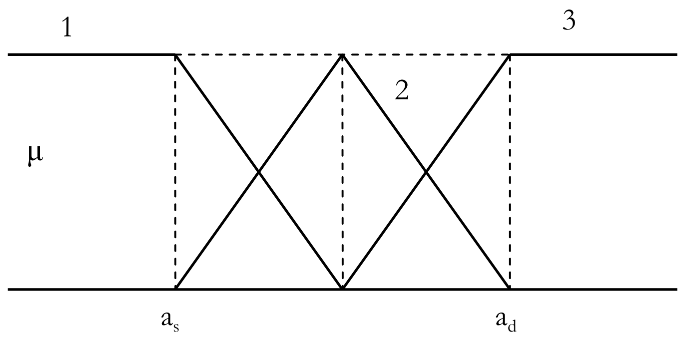

Fig. 3. Fuzzy logic-based ontology dynamics representation.

In accordance with eq. (14) and Fig. 3 the next classification is possible:

If $a<a_s$ the ontology is static.

If $a_s \le a \le a_d$ the ontology is quasi-dynamic.

If $a>a_d$ the ontology is dynamic.

Esch ontology in this interpretation at every stage of its own life cycle (Fig. 1) belong to certain of membership functions μ_1, μ_2 or μ_3 (Fig. 3). This extension of the notion of ontology dynamics considers some useful constructive peculiarities, which will be discussed bellow.

The ontology properties “dynamics” and “fuzziness” are orthogonal and could be presented as shown in Fig. 4.

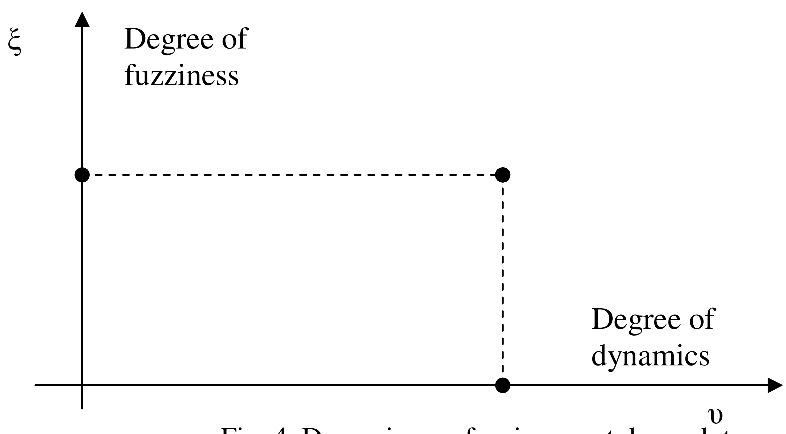

Fig. 4. Dynamics vs. fuzziness ontology plot.

The degree of fuzziness ξ is normalized similarity measure, in accordance with the eq. (7)

$$\xi = \frac{\rho}{\Delta\Psi_{ij}^{\max}}, \qquad 0 \le \xi \le 1, \tag{15}$$

where $\Delta\Psi_{ij}^{\max}$ is the biggest distance between the corresponding pairs from compared ontologies.

The degree of dynamics υ is defined as a relative average speed of dynamic changes represented in the form:

$$\upsilon = \frac{\sigma_{\Delta S}}{\sigma_S}, \tag{16}$$

where:

S(k) is the ontology state in the time k,

$$\sigma_{\Delta S} = \sqrt{\frac{1}{L+1}\sum_{i=1}^{L}\Delta S^2(k+i)} \tag{17}$$

$$\Delta S(k+i) = S(k+i) - S(k+i-1) \tag{18}$$

$$\sigma_{\Delta S} = \sqrt{\frac{1}{L+1}\sum_{i=1}^{L}(S(k+i) - S_m(k))^2} \tag{19}$$

$$S_m(k) = \frac{1}{L}\sum_{i=1}^{L} S(k+i) \tag{20}$$

At the point A in the Fig. 4 the ontology O_A is static and crisp one, and in the arbitrary point B the ontology O_B is dynamic and fuzzy one. During different stages of ontology life cycle represented in Fig. 1, the state S(k) could take up different location in the plain (υ,ξ).

It could be clearly emphased that the state of quasi-dynamic ontology S(k+1), which is updated incrementally, don't depend on previous states S(k), S(k-1), … unlike the real dynamic ontologies, where

$$S(k+1)=f(S(k), S(k-1),\dots,S(k-l)), \tag{21}$$

where l is dynamic memory interval of the ontology.

B. Dynamic ontologies classification

One could distinguish a certain kinds of dynamic ontologies:

- Time Invariant Ontologies (TIO). They possess invariant in time structure and parameters. Dynamic ontology changes are due to numerical values of some FOM elements changes.
- Time Variant Ontologies (TVO). They have changeable in the time characteristics. This kind of ontology is always dynamic.
  For both TIO and TVO the dynamics is a property of the ontology itself.
- Combined dynamic ontology (CDO) is an union of TIO and TVO CDO=<TIO∪TVO>

- Dynamic ontology system (DOS), composed of a number by parametric static ontologies $O_i(\lambda_i)$, which depend on certain gain scheduling indicators λ_i. This indicators are defined by recognition system and through multiplexor could select corresponding parametric static ontology $O_i(\lambda_i)$ as it is shown in Fig. 5

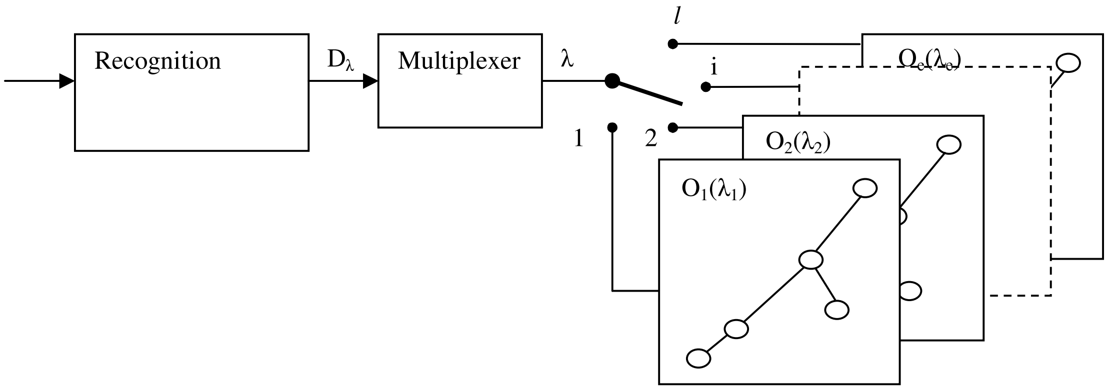

Fig. 5. Quasi-dynamic ontology scheme.

By means of this approach using multiple partial static ontologies $O_i(\lambda_i)$ a dynamic behavior of a global ontology could be presented with the next advantages:
1) The on-line procedures dramatically decrease at the expense of big volume of previous off-line calculations. In this way the processing with ontology is very fast.
2) All measures usable for static ontologies and up to day well developed and established (e.g. consistency, completeness, sensitivity, extendibility, redundancy [1, 2, 8, 12, 13]) could be applied directly using existing software (e.g. Ontoclean [1, 2]).
3) A part or all of the partial static ontologies $O_i(\lambda_i)$ could be fuzzy ontologies which strongly make easier the interpolation between discrete values of the gain scheduling parameter $\lambda_i(\lambda_i \leq \lambda \leq \lambda_{i+1})$.

IV. Origin of dynamics in the ontologies

The prerequisites of dynamic ontologies implementations could be divided in two big groups:
1) External, connected mainly with certain changes of the requested service (query, information, retrieval, e-learning, control), e.g.:
   a) Appearance of unexpected user's needs.
   b) Changes in the preferences of the user.
   c) Unforeseen changes in the environment (industrial, societal, financial etc.).
   d) Significant changes of the solving problem.
   e) A change of the method for solving the running problem.
2) Internal caused by internal changes with the ontology, namely:
   a) A change in conceptualization.
   b) Changes in ontology structure.
   c) Changes in FOM's elements.

d) Changes in FOM element's parameter values.

These changes could be provoked by:

- Knowledge enrichment and accumulation using different techniques and technologies.
    - Data mining and features discovery in data bases.
    - Learning and adaptation.
    - Identification and parameter estimation.
- Application of relevant ontology concepts layers at different stages of the problem solving.

The ontology dynamics could have different origin:

1) *Apriority postulated* dynamics as a significant property, for instance multiple ontology based on a set of static ontologies (Fig. 5).
2) *Inspired* by incremental updating of quasi-dynamic ontologies, when the metric characteristics show that the accepted similarity condition is violated (eq. (14)).
3) *Automatically generated* dynamics in ontologies with procedurally determined elements of the FOM as a function of a gain scheduling time varying parameter $\lambda(k)$ e.g. $X(\lambda(k))$ or indirect dependence on the time e.g. X(k), R(k), A(k).
4) *Experimentally* evaluated dynamics of ontology via determination of its metric and semantic characteristics in a case of implicit changes of the FOM components. In this way new dynamic properties could be discovered and modeled by dynamic ontology like:
    a) New technological trends.
    b) New market dynamics.
    c) New evolving and disappear area.
    d) Changes in user ontologies.

Thus the ontology dynamics could be implicit and to determine it a special procedures are needed in order to calculate its metric characteristics and fuzziness.

Internal processing into the ontologies as a source of dynamics is in the beginning of their investigation. The main recognized problems here consist in:

- In conceptualization – processing new information in order to add and verify new concepts, rejection of certain preliminary accepted, concepts, remove redundancies, put away the ambiguity.
- Recognizing the ontology dynamics via
    - Similarity/distance measure estimation
    - Diagnosis of dynamic behavior
    - Dynamics isolation in accordance with the FOM elements
    - A new dynamic state S(k+1) determination.
- Ontology factorization on a static and a dynamic part

  $O(k)=<O_S,O_D(k)>$,

  where

  O_1 is a static part of the ontology,

  $O_2(k)$ is a dynamic part of the ontology.
- Ontology factorization on consensual and nonconsensual part as each of them could involve static and dynamic subparts (Fig. 6).

These bidirectional factorizations represent a dynamic process, regardless of dynamic parts O_{11} and O_{22} existence in the final ontology. The factorization is accompanied by intensive processes stretched in the time.

	Static	Dynamic
Consensual	O_{11}	O_{12}
Unconsensual	O_{21}	O_{22}

Fig. 6. Hybrid ontologies alternatives.

- Ontology improvement through refinement, elimination of inconsistencies and contradictions, merging, redundancy removal [7, 12, 13]. The considered above internal processes in ontologies show that static and dynamic ontologies are not alternative notions, but could represent different stages of the ontology life cycle (Fig. 1). Here could be a variety of situations, for instance.
- From the beginning the initially static ontology evolves as dynamic one through internal procedures while reaches a new static state, valid for a relatively long time S(k)=S(k+r).
- Initially dynamic ontology could be simplified up static one, if the dynamic effect could be neglected and one doesn't require very height accuracy.
- A given concept could be in fact dynamic or fuzzy, but in the reasoning it is accepted as static and crisp.
- All known metric characteristics of the dynamic ontologies represent quasi-static estimations, which are valid only for fixed time instances.
- A certain reasoning procedures in the beginning could be accomplished for crisp/static models of ontology, but after wile fuzzy, approximate or dynamic models should be used.

Consequently the four main ontology characteristics (static-dynamic, crisp-fuzzy) must be considered in unity (Fig. 7).

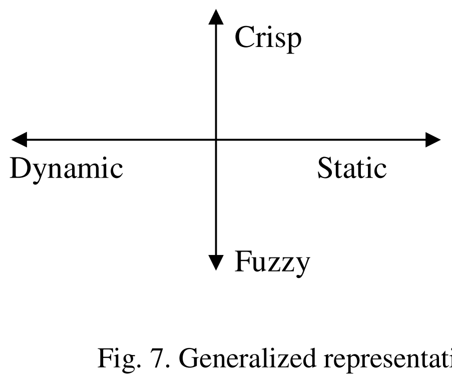

Fig. 7. Generalized representation of ontology.

V. Generalized dynamic ontologies

A. Definition

Generalization of dynamic ontologies covers the next understanding:

- Ontology dynamics could be considered as a stage of their life cycle (Fig. 1): beginning, development, utilization, refinement, maintenance.
- Dynamics could be a possible property both for isolated ontology, as well as for ontology system (ontology set, composite ontology).
- The threshold as a distance/similarity measure dividing static and dynamic ontologies could be chosen with different values in the separate stages of the certain sophisticated problems solving. Thus the same ontology could be considered as static or as dynamic depending on accepted algorithm in order to reduce computational load.
- The possibility to consider dynamics in terms of fuzzy sets.
- Adaptation of possible nonhomogeneonity of ontologies in different aspects:
    - One part of the ontology is static, the rest is dynamic.
    - Some of the FOM components are static and the rest are dynamic.
    - A certain FOM-elements are represented in declarative way and some of them – in procedural way.
    - The FOM-elements could be given as crisp, fuzzy or interval variables, relations or restrictions.
- A given dynamic ontology system could be heterogeneous regard to thresholds of dynamics, degree of accuracy, representativity, level of abstraction, structure.

B. Usefulness of generalized dynamic ontologies

An introduction of the generalized dynamic ontologies is useful in the following broad directions:

- To help more general theoretical consideration of ontologies in static, quasi-static and dynamic conditions.
- To extend application of ontology approach in variety of systems with real dynamics – technical, biological, social.
- To reveal new research problems in a poor studied and clearly interdisciplinary area.

Generalized dynamic ontologies (GDO) would give strong advantages and in a numerous more concrete problems in ontological engineering:

1) GDOs are suitable in ontology-based systems with iterative procedures for instance.
    a) Systems with personalized information retrieval.
    b) Iteration-based control systems (model predictive control, ant colony optimization).
2) GDOs are effective in the earlier stages of conceptualization for a rough intelligent filtration of subclasses, relations, attributes.
3) GDOs increase the internal processing in the ontologies themselves using relevant strategies for improving.

4) GDOs are a useful approach for subsystems forming the whole ontology depending on the degree of dynamics – slow, average and fastly changeable – in order to realize temporal decomposition.
5) GDOs help organization of two stage procedure in order to solve whole problem in the ontology-based system with partially conformity ontology:
   a) On the base of consensual part of the ontology to solve corresponding part of the whole problem.
   b) Using intelligent autonomous agent to solve the rest of the problem using nonconsensual part of the ontology.
6) Via GDO could be organized selective operations in the Truth Maintenance System (TMS) via localization the procedures on dynamic parts with highest dynamics.
7) Trough GDOs the communication load due to the interoperability into the hybrid agent/ontology based information and control systems could be strongly reduced in accordance with the rate of changes into the partial ontology states.
8) Via GDOs only part of dynamic ontologies could be activated depending on the degree of dynamics according the adopted system of thresholds.

VI. Conclusions

The state of ontology is fundamental notion, which could be constructively used for similarity/distance metrics formation in changeable ontologies.

Origins of dynamics in ontologies are numerous and they have very different character.

The properties “dynamics” and “fuzziness” are not a priori given, rather must be recognized by using ontology similarity metrics.

The controversial attributes “static-dynamic” and “crisp-fuzzy” could be considered as a different possible behavior of the same ontology.

The proposed generalization of the notion “dynamic ontology” allows traditional static ontologies to be considered as dynamic ones into their self changes during sequential stages of the ontology life cycle. This generalization was found to be practically useful.

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