ANALOGOUS REASONING AND CASE-BASED REASONING FOR INTELLIGENT DECISION SUPPORT SYSTEMS

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***Abstract**: Methods of analogous reasoning and case-based reasoning for intelligent decision support systems are considered. Special attention is drawn to methods based on a structural analogy that take the context into account. This work was supported by RFBR (projects 02-07-90042, 05-07-90232).*

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1. Introduction

Investigation of mechanisms that are involved in the analogous reasoning process is an important problem for specialists in artificial intelligence (AI). The analogy can be used in various applications of AI and for solving various problems, e.g., for generation of hypotheses about an unknown subject domain or for generalizing experience in the form of an abstract scheme. AI experts model analogous reasoning by computers in order to develop more flexible models of search for solutions and learning. The great interest in this problem is caused by the necessity of modeling human reasoning (common sense reasoning) in AI systems and, in particular, in intelligent decision support systems (IDSS).

In this paper, we consider approaches and methods of search for solutions based on structural analogy and cases, which are oriented to use in real-time (RT IDSS). These systems are usually characterized by strict constraints on the duration of the search for the solution. One should note that, when involving models of analogous reasoning in IDSS, it is necessary to take into account a number of the following requirements to systems of this kind [1]:

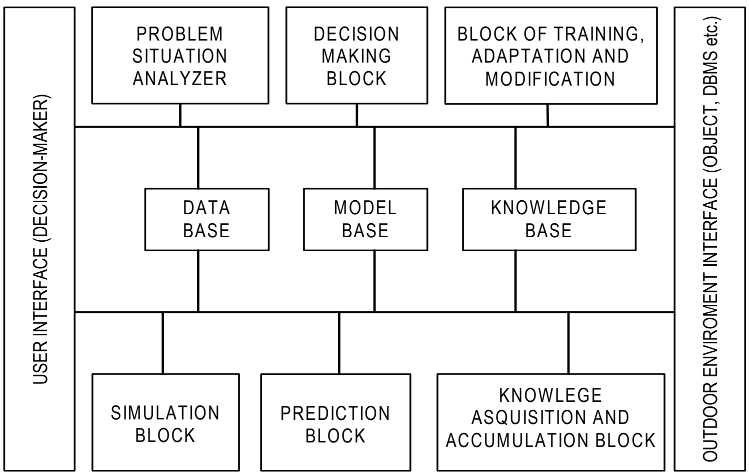

Fig. 1 Base RT IDSS structure

- The necessity of obtaining a solution under time constraints defined by real controlled process;
- The necessity of taking into account time in describing the problem situation and in the course of the search for a solution;
- The impossibility of obtaining all objective information related to a decision and, in accordance with this, the use of subjective expert information;

- Multiple variants of a search, the necessity to apply methods of plausible (fuzzy) search for solutions with active participation of a decision making person (DMP);
- Nondeterminism, the possibility of correction and introduction of additional information in the knowledge base of the system.

The generalized structure of a RT IDSS [2] is given in Fig. 1.

The search for an analogy-based and case-based solution may be applied in units of analysis of the problem situation, search for solutions, learning, adaptation and modification, modeling, and forecasting. The use of the respective methods in IDSS broadens the possibilities of IDSS and increases the efficiency of making decisions in various problem (abnormal) situations.

Special attention in this paper will be paid to the most efficient inference methods on the basis of structural analogy that take into account the context and rest on the structure mapping theory.

2. Analogous Reasoning

Questions about the nature of analogies, a formal definition, justification of reasoning by analogy, etc., arose in the time of epicureans and stoics. The attempts to answer these questions, starting from the first attempts of Leibniz to formalize this notion up to our time, have not received a final answer [3-4].

In encyclopedia the word analogy (analogia, Greek: correspondence, similarity, likeness, closeness) is defined as the similarity of objects (phenomena, processes) with respect to some properties. Reasoning by analogy is the transfer of knowledge obtained from an object to a less studied one, which is similar to the latter with respect to some essential properties or attributes. Thus, analogous reasoning can be defined as a method that allows one to understand a situation when compared with another one [4-6]. In other words, an analogy is an inference method that allows one to detect likeness between several given objects due to transfer of facts and knowledge valid for both objects, to other objects and to determine a means of problem solution or to forecast unknown properties. It is this type of inference that is used by a human in the first stages of solving a new problem.

Notwithstanding the fact that the method of analogy is intuitively clear to everyone and is actively used by humans in everyday life, the notion of analogy does not allow for complete formal definition and, hence one cannot uniquely describe the mechanism of reasoning by analogy. At the present time, there are a great number of various models, schemes, and methods that describe mechanisms of analogous reasoning [3-13].

Analysis of the literature has shown that one can distinguish various types of analogies [4-6]. Depending on the nature of information transferred from an object of an analogy to the other one, the analogy of properties and that of relations can be distinguished.

The analogy of properties considers two single objects or a pair of sets (classes) of homogeneous objects, and the transferred attributes are properties of these objects, for example, an analogy between illness symptoms of two persons or an analogy in the structure of the surfaces of Earth and Mars, etc.

The analogy of relations considers pairs of objects, where the objects can be absolutely different and the transferred attributes are properties of these relations. For example, using the analogy of relations, bionics studies processes in nature in order to use the obtained knowledge in modern technology.

According to plausibility degrees one can distinguish three types of analogies: strict scientific analogies, nonstrict scientific analogies, and nonscientific analogies.

A strict scientific analogy is applied to scientific studies and mathematical proofs. For example, the formulation of the attributes of the similarity of triangles is based on a strict analogy, which results in a deductive inference, i.e., which deduces a valid conclusion.

Unlike the strict analogy, a nonstrict scientific analogy results only in plausible (probable) reasoning. If the probability of a false statement is taken equal to 0 and that of the true statement is taken equal to 1, then the probability of inference by a nonstrict analogy lies in the interval from 0 to 1. To increase this probability, one need to satisfy a number of requirements to the method of reasoning by analogy, otherwise, a nonstrict analogy may become nonscientific.

The probability of conclusions by a nonscientific analogy is not high and often is close to 0. A nonscientific analogy is often used deliberately to perplex the opponent. Sometimes, a nonscientific analogy is used unintentionally, by someone not knowing the rules of analogies or having no factual knowledge concerning the objects and their properties that underlie the inference. For example, nonscientific analogies underlie superstitions.

3. Case-based Reasoning

Case-based reasoning, like analogous reasoning, is based on an analogy; however, there are certain differences in their realizations [5-8]. In most encyclopedias precedent (from Latin, precedentis) is defined as a case that took place before and is an example or justification for subsequent events of this kind. To create a precedent means to give grounds for similar cases in the future, and to establish a precedent is to find a similar case in the past.

As the practice shows, when a new problem situation arises, it is reasonable to use this method of case-based reasoning without drawing an analogy. This is caused by the fact that humans operate with these reasoning schemes at the first stages, when they encounter a new unknown problem.

Case-based reasoning is an approach that allows one to solve a new problem using or adapting a solution of a similar well-known problem. As a rule, case-based reasoning methods include four main stages that form a CBR-cycle, the structure of which is represented in Fig. 2 [8].

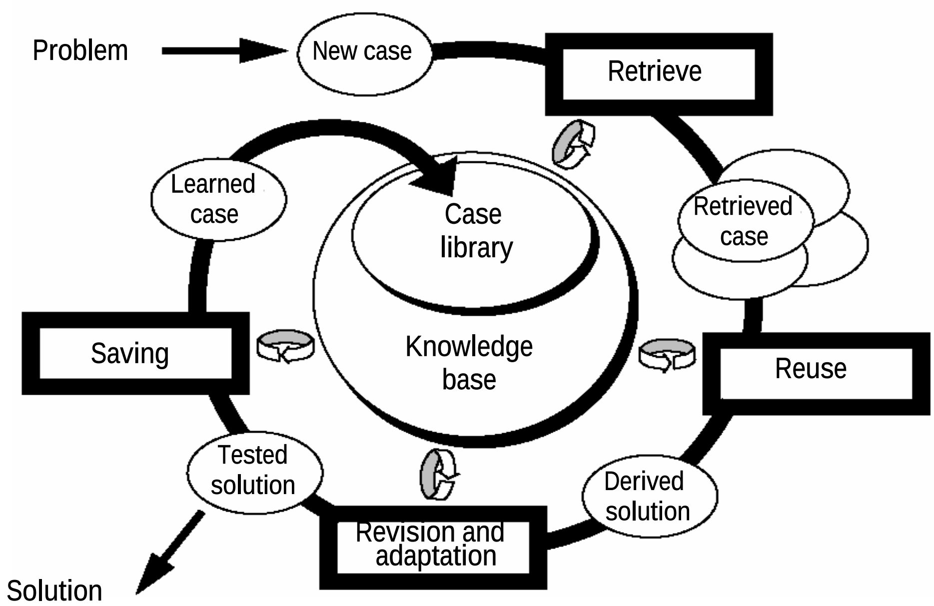

Fig. 2 The structure of CBR-cycle

The main stages are as follows:

- Retrieving the closest (most similar) precedent (or precedents) for the situation from the library of precedents;
- Using the retrieved case (precedent) for solving the current problem;
- If necessary, reconsidering and adaptation of the obtained result in accordance with the current problem;
- Saving the newly made solution as part of a new case.

It is necessary to take into account that a solution on the basis of precedents may not attain the goal for the current situation, e.g., in the absence of a similar (analogous) case in the case library. This problem can be solved if one presupposes in the CBR-cycle the possibility to update the case library in the reasoning process (inference) [5]. A more powerful (in detecting new facts or new information) method of search for a solution on the basis of analogy is a means of updating case libraries. We also note that the elements of case-based reasoning may be used successfully in analogy-based reasoning methods [7]; i.e., these methods successfully complement each other and their integration in IDSS is very promising.

In what follows, we consider in detail the methods of search for a solution on the basis of structural analogy, which allows one to take into account the context and are based on the structure mapping theory. We use semantic networks (SNs) as a model of knowledge representation.

4. Knowledge Representation in the Form of a Semantic Network for Analogous Reasoning

The choice of an SN for knowledge representation is due to an important advantage, which distinguishes it from other models, such as natural representation of structural information and fairly simple renewal in a relatively homogenous environment. The latter property is very important for RT IDSSs oriented to open and dynamical subject domains.

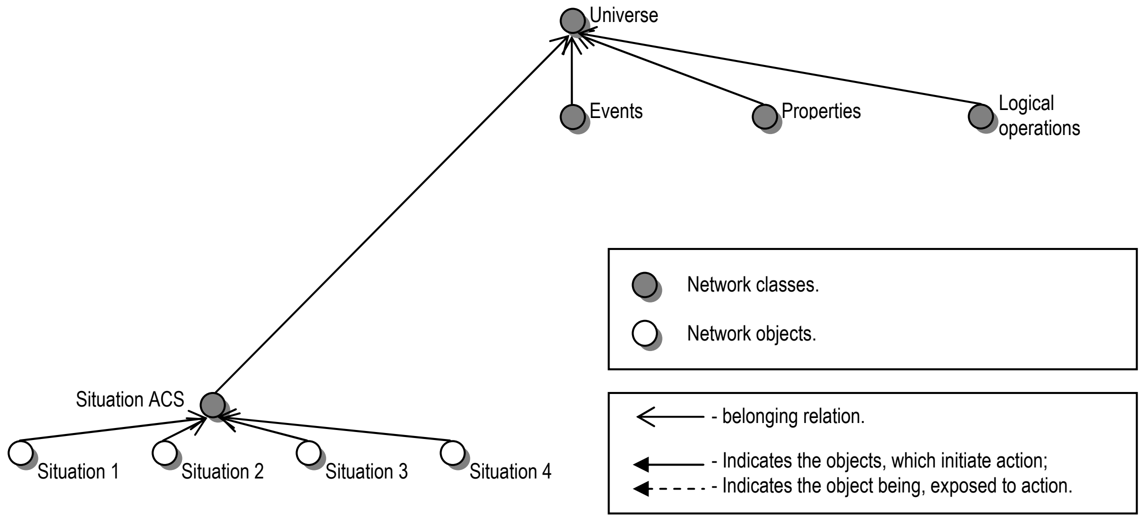

Fig. 3 (a) A fragment of the semantic network that represents the metalevel

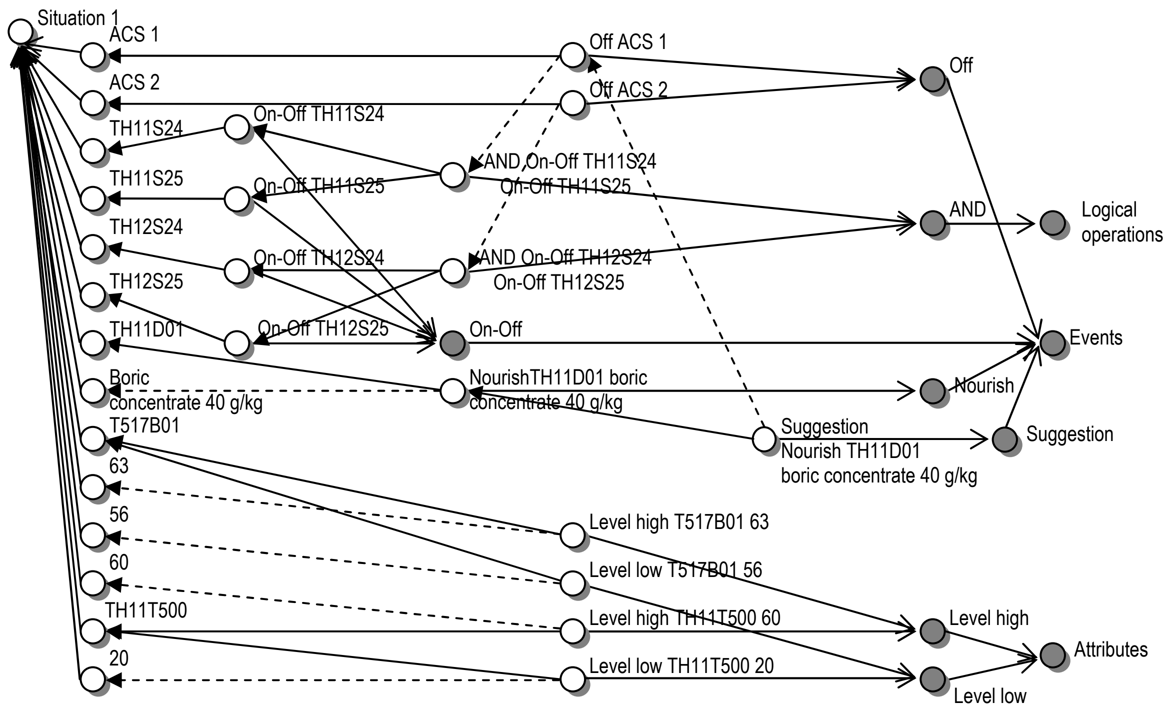

Fig. 3 (b) A fragment of the semantic network that represents the Situation 1 that was formed in the course of ACS functioning

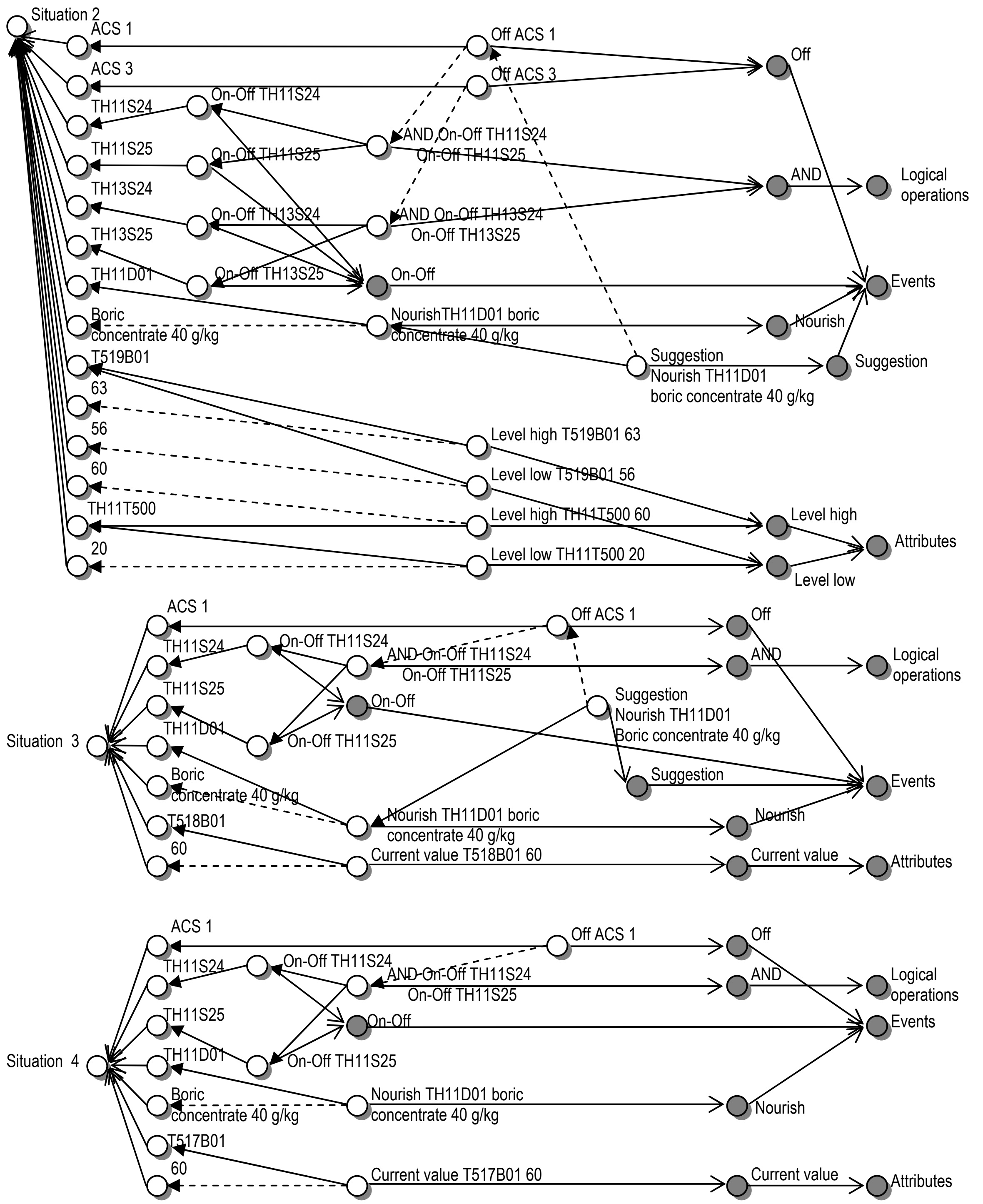

Fig. 3 (c) A fragment of the semantic network that represents the situations (Situation 2, Situation 3, Situation 4) that were formed in the course of ACS functioning

A semantic network is a graph <V,E> with labelled vertices and arcs, where V and E are sets of vertices and arcs, respectively. The vertices can represent objects (concepts, events, actions, etc.) of the subject domain, and the arcs represent the relation between them.

We consider the structure of the SN in more detail using an example from power engineering -operation control of nuclear power unit (Fig. 3).

We give a semantic interpretation of the information given in the SN for Situation 1 (Fig. 3b):

- It is recommended to inject TH11D01 with boric concentrate 40 g/kg caused by switching off ACS 1 (automatic cooling system) due to closing the gates TH11S24 and TH11S25;
- ACS is switched off due to the closed gates TH12S24 and TH12S25;
- The upper setting T517B01 (pressure in the container of ACS 1) is equal to 63;
- The lower setting T517B01 (pressure in the container of ACS 1) is equal to 56;
- The upper setting TH11T500 (temperature in the frame of ACS 1) is equal to 60;
- The lower setting TH11T500 (temperature in the frame of ACS 1) is equal to 20.

5. Search for a Solution on the Basis of Structural Analogy Taking into Account the Context

In [9] it was proposed to consider an analogy as a quadruple A = <O, C, R, P>, where O and R are the source object and the receiver object and C is the intersection object, i.e., the object that structurally intersects the object source and object receiver, which has a larger cardinality of the set of properties as compared with these objects. In other words, the analogy between the source object and receiver object is considered in the context of the intersection, and P is the property for definition of the original context. The structure of this analogy is represented in Fig. 4.

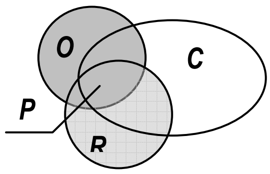

Fig. 4 Structure of analogy using the context

Using the described structure of the analogy, the authors of [9] propose an algorithm for the problem solution that is based on an analogy of the properties. An SN with information about the subject domain, a receiver R, and the property for defining the original context P provide input data for this algorithm.

The algorithm for the problem solution on the basis of an analogy taking into account the context consists of the following steps.

Step 1. Determine all objects of the SN, except for receiver R, that have property P. If there are no objects of this kind, then the search for a solution fails (without finding an analogy), otherwise, go to step 2.

Step 2. For the objects found in step 1, determine all possible intersections of C with R taking into account P. If there are no intersections of C, the first search for a solution fails, otherwise, go to step 3.

Step 3. From the objects extracted in step 1, determine all possible sources O for analogies with the receiver R and the intersection C taking into account P. In the case of success (possible analogies for R are defined), go to step 4, otherwise, the search for a solution fails.

Step 4. From the analogies extracted in step 3, choose the most appropriate (taking into account the requirements of the DMP). In the case of success, go to step 5; otherwise, the search for a solution fails.

Step 5. The analogies obtained in step 4 (which could be previously compared with each other taking into account the context) are given to the DMP, which means successful termination of the algorithm.

Having obtained analogies, the DMP may then make the final choice of the best ones. On the basis of these facts, the facts (properties) that hold for the source O are transferred to the receiver R.

Consider a modified algorithm for a problem solution that uses the structural analogy based on the modified structure of an analogy and the algorithm for the search of minimal intersections [5, 6]. The modification consists in the fact that P is considered not as a unique property, but as a set of properties that determine the original context of the analogy.

As compared with the base variant, one of the main advantages of this modified algorithm is the possibility of realizing the search for a solution on the basis of an analogy without refining the original context, since in the result of the search for the minimal intersection, one can easily distinguish all possible contexts for the analogy. For example, if it is necessary to find analogues for Situation 4 (Fig. 3c), then, for the base algorithm, one should indicate property P to determine the original context (e.g., the property "Switch off ACS") since in the result analogues will be obtained in all possible contexts. Another important advantage of the modified algorithm is the possibility of a more detailed refinement of the original context for the determination of analogies; i.e., as P, one can choose several properties (e.g., "Switch off ACS" and "Switch off-Close TH11S24"). This is especially important in the work with a complex object, when one should operate with large amount of information, since the more detailed the original context, the faster the search for a solution on the basis of analogies will be realized and the more qualitative the solution obtained will be. Moreover, in the modified algorithm there is a possibility to construct an analogy taking into account the context between well-known objects, the source and the receiver.

Thus, in the execution of the modified algorithm the procedure of searching for minimal intersections is used. In turn, the minimal intersections determine the context for the analogy. At the second stage, depending on the fact whether an object source and a property or a set of properties are given, or there is no refinement of the original context from objects that are contained in the set of generators of minimal intersections, analogies are formed. In the case of successful termination of the search for a solution on the basis of analogies, new facts for the receiver object will be obtained.

6. Search for Solution on the Basis of an Analogy Based on the Structure Mapping Theory

Structure mapping theory (SMT) allows one to formalize the set of implicit constraints, which are used by the human who operates notions such as analogy and similarity [10]. This theory uses the fact that an analogy is a mapping of knowledge of one domain (base) in another domain (target) based on the system of relations between objects of the base domain, as well as the target domain. The main principle of SMT is that of a systematic character, which reflects the fact that humans (DMP) prefer to deal with a system of connected relations, not just with a set of facts or relations.

According to SMT, the inference process on the basis of analogies consists of the following stages.

1) Definition of potential analogies. Having the target situation (target), define another situation (base) that is analogous or similar to it.

2) Mapping and inference. Construct a mapping that consists of matches between the base and the target. This mapping can contain additional knowledge (facts) about the base that can be transferred to the target. These pieces of knowledge are called candidates of conclusions formed by an analogy.

3) Estimate the match "quality." Estimate the correspondence found using structural criteria such as the number of similarities and differences, the degree of structural correspondence, and the quantity and type of new knowledge synthesized by analogy from the conclusion candidates. We stress that the estimate of the "quality" of matching in SMT is based only on structural criteria that distinguish analogies from other types of inference.

Besides analogies, other types of likeness based on structurally compatible mapping can be represented in SMT. In the case of an analogy, only structures of relations are mapped, while the properties of objects that do not play role in the structure of relations are ignored. In strict likeness both the structures of relations and the properties of objects are mapped. In purely external matching, object properties are mapped (e.g., as in the metaphor "The road is like a silver band"), and in abstract mapping the entities in the base domain are not objects, but some variables.

Consider the structure mapping engine (SME) which is based on SMT [11-12]. This mechanism is suited for modeling inference by an analogy providing the match of an estimate independent of the subject domain. The input data for the SME algorithm are structural representations of the base and target domains.

Algorithm SME consists of the following steps:

Step 1. Constructing local mappings. Determine the matches (mapping hypotheses) between separate elements in the base and target domains by means of the following rules:

(1) If two relations have the same name, then create a mapping hypothesis.

(2) For the mapping hypothesis between relations, test the arguments: if they are objects or functions, then create for them local mapping hypotheses. Determine the plausibility estimates for these local hypotheses using the following rules:

(a) increase the plausibility degree for the correspondence if the base and the target relations have the same names;

(b) increase the plausibility degree for the correspondence if it is known that the base relation has the parent relation.

Rule (a) prefers the identity of relations, and (b) reflects the principle of the systematic character of relations.

Step 2. Construction of global mappings. Form mapping systems that use compatible pairs of objects (Emaps). Unite them in systems of relation with compatible mapping of objects. With each global mapping of this kind (Gmap), relate the set of conclusion candidates.

Step 3. Construct conclusion candidates. For each mapping Gmap, construct a set of the facts (possibly empty) that occur in the base domain, which does not occur originally in the target domain.

Step 4. Estimate of global matches. The global matches receive a structural estimate that is formed taking into account the plausibility of local correspondence. Terminate.

Thus, as a result, the most systematic consistent mapping structure Gmap that includes the following components arises: matches is set of paired mappings between base and target domains; conclusion candidates is the set of new facts that presumably are contained in the target domain; structure estimate is a numeric equivalent of the match quality based on the structural properties of Gmap.

The main advantages of SME that are especially important for RT IDSS are the polynomiality of the considered SME-algorithm and the simplicity of importing the conclusion candidates in the target domain. Note that this mechanism is used in a number of research systems (in the domain of plausible inference on the basis of analogies), in particular, in the systems ACME, LISA, IAM, Sapper, CyclePad, PHINEAS [12].

7. Conclusion

Methods of the search for a solution on the basis of a structural analogy and cases were considered from the aspect of their applications in modern IDSS, in particular, for a solution of problems of real-time diagnostics and forecasting. Methods based on analogies of properties and relations were described. An example of an algorithm for the search of a solution on the basis of an analogy of properties that takes into account the context was proposed. A more efficient algorithm, in the sense of the solution quality, is proposed. It uses a modified structure of an analogy that is capable of taking into account not one property (as in the base algorithm), but a set of properties. These properties determine the original context of the analogy and transfer from the source to the receiver only those facts that are relevant in the context of the constructed analogy.

We stress once again that analogous reasoning can be used both for solution of well-formalized problems and for the problems of search forecast (as is done, e.g., in the JSM-method of automated hypothesis generation [13]). In other words, analogous reasoning is an approximate inference rule based on heuristic mechanisms. Therefore, any solutions obtained with the use of it should be amplified by reliable methods of reasoning if their use is planned for making important decisions or actions.

The presented method was applied in realization of a prototype of a RT IDSS on the basis of nonclassical logics for monitoring and control of complex objects like power units.

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