Accelerated Logical Inference in the Intelligent Control Systems

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Abstract. We considered the features of the intellectual approach to the development of complex objects control systems. Was selected the mathematical apparatus of the logical inference theory as a basis for describing the functioning of the inference machine - the main module of intellectual control system. In order to increase the efficiency of this module was offered the deductive method of logical inference by the disjuncts dividing based on defining literals. Was described the procedure of performing logical inference from the formation of the original data to achieving a breakpoint. Process of logical inference by dividing the disjuncts (clauses) on the basis of defining literals is illustrated by an example. Application of this method will reduce the number of vertex of the decision tree that require processing, and thus significantly improve the performance of intelligent control system of complex technical objects.

Introduction

The creation of intelligent control systems (CS) today is widely recognized as a promising area of research. The theory of these systems and their applications are reflected in the works of leading scientists, such as D.A. Pospelov [1], Y.-Z. Lu [2], Zi-Xing Cai [3], K.M. Hangos [4], I.M. Makarov [5], A.A. Zhdanov [6]. However, theoretical and applied bases of intelligent CS are far from complete, including in the area of development of monitoring and control systems of sophisticated technical and human-technical objects. Such control systems include in their composition a decision support sub-systems comprising different solvers (inference machines, artificial neural networks) and usually operate in difficult conditions. In this case, large dimensions of the controlled object, its unsteadiness, the distribution of parameters, its nonlinearity and the variety of arising situations, lack of control of external influences, the presence of coarse interference and the variability of objectives, criteria and limits are assumed as the difficult conditions.

Significant increase of efficiency of complex objects management can be achieved by applying adequately complex information-operating systems, and that is the intelligent situational management system [1]. Situational management is a method of managing of complex technical and organizational systems, based on the ideas of artificial intelligence theory: representation of knowledge of the controlled object and its management methods at the level of logical-linguistic models, the use of learning and generalization as basic procedures in the construction of the control algorithms on the current situation, the use of deductive systems for the construction of multi-step solutions.

Today intelligent CS become an integral part of these areas of human activity as the control of industrial processes [7], energy-saving, the transport sector, medical and technical diagnostics [8], formal verification of software systems [9], information security and the intensively developing market of "Internet of Things" (including "smart home" systems) [10]. In most cases, the functioning of such systems is to find the optimal transitions in the complex, highly branched, state graph of controlled object. Therefore, a popular mathematical apparatus for building intelligent CS is the theory of logical inference, with the majority of applications can be formalized as the calculus of first-order predicates [11,12].
The undoubted benefits of methods of logical inference include the possibility of significantly reducing the time to receive solutions to problems that require the processing of structures with a large number of states, for example, a decision tree in data analysis for predictive models. This is achieved through the use of highly effective heuristics to significantly reduce the number of the nodes of the tree that require processing.

However, one of the fundamental problems that limit the use of the apparatus of logical inference theory is the algorithmic unsolvability of determining the moment of completion of the inference [13]. It is impossible to determine by formulation of the problem how many steps are required to obtain the solution, and in the worst case, the complexity of the output will be comparable to the complexity of exhaustive search, which is not always acceptable.

In this context it becomes an urgent task of search of the heuristic mechanisms and principles that reduce the time of finding of the solution that satisfies the specific requirements (optimal for the given requirements).

**Logical Inference by the Division of Disjuncts**

An example of one of the most productive methods of deductive inference is the method of the disjuncts division, which is based on the eponymous procedure [14]. The formal definition of the operation of disjuncts division and description of the classical method of logical inference, which is a combination of sequential processes: procedures of the forming of remainders, procedures of the disjuncts division and the procedures of the inference contained in [14]. The main features of the method are the high degree of parallelism and a weak dependence of performed operations by the data, which determines its advantage in speed. Furthermore, the method is bidirectional, which also allows to find a solution, on average, half the time - two times faster than with the use of analogical methods. Due to the high speed of the inference, this method has been used successfully in various fields of human activity: the forecasting of the situations progress, medical and technical diagnostics, adaptive control, verification of program management systems, etc. [15]. The family of specialized accelerated parallel inference methods has been developed based on the basic operation (operation of disjuncts division).

In general, the problem solved by this method can be formulated as follows. Suppose there is a knowledge base \( KB = KBr \cup KBf \), where \( KBr \) - a set of rules, as well \( KBf \) - a lot of facts (one-literal disjuncts). The elements \( D_i, \quad i = 1..|KBr| \) of the set \( KBr \) are disjunctive rules \( D_i = L_1 \lor L_2 \lor ... \lor L_{|D_i|} \). It is required to set hatchability (truth) of the target statement \( d \), also represented in the form of a disjunct.

Finding the solution is carried out by dividing all the knowledge base rules by the original goal statement. As a result of the inference step can be obtained disjuncts - the remainders. After applying to the conjunction of these remainders the separation rules - the connection and transfer rules [14], the new inference rules are being generated. Thus, the problem of determining the validity of the initial target statement reduces to the problem of establishing hatchability of formed at each step the subsidiary rules-conclusions. The process continues as long as there is no proof of the falsity of at least one of the inference statements or in case of successful completion of the inference, the truth of the original goal statement.

Geometric interpretation of the reviewed process is shown in Figure 1. Generation of new inference rules is carried out until it reaches a breakpoint (successful or unsuccessful completion of the inference).
Obviously, one of the most effective ways of reducing the time to perform the entire procedure of inference is to reduce the number of generated target statements [16]. It is possible to use the metadata on the domain and do not form part of the possible remainders. Determination of remainders, the use of which is unsound in terms of further inference progress, it is proposed to carry out as follows.

Method of Accelerated Logical Inference by the Disjuncts Division on the Basis of the Defining Literals

Suppose there is a knowledge base $KB = KBr \cup KBf$, where KBr - a set of rules, as well KBf - a lot of facts (one-literal disjuncts). Moreover, the elements of the set $KBr = \{<D_i, O_i>, \ i = 1..|KBr| \}$ are two-element tuple, including disjunctive rule $D_i = L_1 \lor L_2 \lor ... \lor L_{|D_i|}$ and the set $O_i$ - a set of positive integers of the range $[1, |D_i|]$. The presence of the element $x \in [1, |D_i|]$ in the set $O_i$ indicates that the literal $L_x$ of the disjunct $D_i$ is "defining". Defining (the "most important") elements are highlighted by the knowledge expert, taking into account the specific characteristics of the problem situation.

Task of the logical inference remains the same - it is used do to set the hatchability (the truth) of the target statement $d$ from the knowledge base $KB$, and $d$ is represented in disjunctive form.

In the course of solving the problem using the proposed method should be done the procedure of the disjuncts division to reach the breakpoint. And carry it out in two stages:

1. Apply the procedure of limited formation of remainders one time.
2. In case of the gaining of the remainders which is not equal to 1 on the first stage, apply the procedure for the complete formation of remainders (possibly repeatedly).

The essence of the first stage is to divide disjunct - dividend $D_i$ belonging to the set of rules of the knowledge base $KBr$ by the disjunct - divider $d$ which is being under inference on this step.

The elements of the remainders matrix are computed as follows. The remainder of the division ($\partial L/\partial L'$) of a disjunct $D_i$ containing a literal $L$, on a literal $L'$ of disjuncts $d$ is:

- $(\partial L/\partial L') = 1$, if the literals $L$ and $L'$ are not unified or the literal $L$ is not defining;
- $(\partial L/\partial L') = 0$, if $L$ and $L'$ are unified and $L$ - single literal in $D_i$;
- $(\partial L/\partial L') = b$, if $L$ and $L'$ are unified and $D_i$ contains more than one literal; remainder $b$ comes out from $D_i$ after excluding the literal $L$ from it and applying corresponding unifying substitution to the remaining literals.

Figure 1. Progress of logic inference process.
On the second stage, when the procedure of the complete formation of remainders is applied, elements of the remainders matrix are calculated similarly, except that the unitary remainder \((\partial L/\partial L') = 1\) can be obtained only when the literals \(L\) and \(L'\) are not unified.

Thus, the insertion of defining literals in the first stage of the procedure of disjuncts division prevents the production of «unpromising» residues. This achieves reduction in the number of new inference disjuncts, truth of which is going to be proven on the next steps of the inference, what results in a significant reduction in the "width" of the tree of the decision search and, accordingly, the number of processed vertexes.

To ensure the effectiveness of the proposed method, it is necessary to correctly identify the elements of the sets \(O_i\). In fact, the non-inclusion of any literals of a disjunct \(D_i\) in a set of defining literals means that it is impractical to prove the truth of these literals via the rule. It is obvious that such a conclusion can be done by an expert only by performing the additional analysis of domain properties.

Geometric interpretation of isolation of groups of defining literals among rules \(KBr\) is shown in Figure 2.

![Figure 2. Progress of logic inference process with the use of defining literals.](image)

As can be seen from the figure, the use of defining literal allows to give the "orientation" to the process of inference, the validity of which is obtained from the specific subject area.

**Example of Accelerated Logical Inference with the Use of the Defining Literals**

The process of logical inference with the use of the defining literals will be illustrated on the following example.

Suppose there is a knowledge base \(KB\) that includes the following rules and facts:

- \(D_1 = P(x) \lor \neg Q(x) \lor \neg R(x, y)\);
- \(D_2 = \neg S(y) \lor \neg T(y) \lor U(y) \lor \neg Z(y)\);
- \(D_3 = Q(x) \lor \neg V(x)\);
- \(D_4 = Q(x) \lor \neg W(x)\);
- \(D_5 = V(x) \lor W(x) \lor \neg K(y)\);
- \(D_6 = T(y) \lor \neg M(y)\);
- \(D_7 = \neg U(y) \lor Y(b)\);
- \(D_8 = W(a) \lor K(y)\);
- \(D_9 = M(x) \lor K(y)\);
- \(D_{10} = \neg Y(b) \lor K(y)\);
- \(D_{11} = Z(y) \lor L(y)\);
- $D_{12} = \neg U(b) \lor E(y) \lor F(y)$;
- $D_{13} = \neg F(y) \lor G(b) \lor K(a)$;
- $D_{14} = \neg L(y) \lor K(y) \lor Z(a)$;
- $D_{15} = \neg L(b) \lor K(y)$;
- $D_{16} = R(a, c)$.

It is required to set the validity of the statement $d = P(a) \lor \neg S(b)$.

Progress of inference process performed with the use of the method of logical inference by dividing the disjuncts is presented in Table 1.

<table>
<thead>
<tr>
<th>The level of the decision tree</th>
<th>Checking statements</th>
<th>Obtained remainders</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$P(a) \lor \neg S(b)$</td>
<td>$\neg Q(a)$ $\neg T(b) \lor U(b) \lor \neg Z(b)$</td>
</tr>
<tr>
<td></td>
<td>$Q(a) \lor T(b)$</td>
<td>$\neg V(a)$ $\neg W(a)$ $\neg M(b)$</td>
</tr>
<tr>
<td></td>
<td>$Q(a) \lor \neg U(b)$</td>
<td>$\neg V(a)$ $\neg W(a)$ $Y(b)$ $E(y) \lor F(y)$</td>
</tr>
<tr>
<td></td>
<td>$Q(a) \lor Z(b)$</td>
<td>$\neg V(a)$ $\neg W(a)$ $L(b)$</td>
</tr>
<tr>
<td>2</td>
<td>$V(a) \lor W(a) \lor M(b)$</td>
<td>$K(y)$ $\neg K(y)$</td>
</tr>
<tr>
<td></td>
<td>$V(a) \lor W(a) \lor \neg Y(b) \lor \neg E(y)$</td>
<td>$K(y)$ $\neg K(y)$</td>
</tr>
<tr>
<td></td>
<td>$V(a) \lor W(a) \lor \neg Y(b) \lor \neg F(y)$</td>
<td>$K(y)$ $\neg K(y)$ $G(b) \lor K(a)$</td>
</tr>
<tr>
<td></td>
<td>$V(a) \lor W(a) \lor \neg L(b)$</td>
<td>$K(y)$ $\neg K(y)$ $K(y) \lor Z(a)$</td>
</tr>
</tbody>
</table>

Inferencing process is completed successfully - because in step 3 received opposing the remainders ($K(y)$, $\neg K(y)$) and therefore the target statement is true. A decision tree consists of three levels and eight vertexes.

Let some of the known laws of the subject area and the rules of the knowledge base $KB$ can be represented by sets $O_i$:
- $O_1 = \{1, 3\}$;
- $O_2 = \{2, 3\}$;
- $O_3 = \{1\}$;
- $O_4 = \{1, 2\}$;
- $O_5 = \{1, 3\}$;
- $O_6 = \{2\}$;
- $O_7 = \{1, 2\}$;
- $O_8 = \{1\}$;
- $O_9 = \{2\}$;
- $O_{10} = \{1, 2\}$;
- $O_{11} = \{2\}$;
- $O_{12} = \{2, 3\}$;
As in the previous case, it is required to establish the truth of statement \( d = P(a) \lor \neg S(b) \). Progress of inference process performed with the use of the method of logical inference by dividing the disjuncts with the use of the defining literals is presented in Table 2.

Table 2. Progress inference process (with the use of the defining literals).

<table>
<thead>
<tr>
<th>The level of the decision tree</th>
<th>Checking statements</th>
<th>Obtained remainders</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( P(a) \lor \neg S(b) )</td>
<td>( \neg Q(a) )</td>
</tr>
<tr>
<td>2</td>
<td>( Q(a) )</td>
<td>( \neg V(a) ) ( \neg W(a) )</td>
</tr>
<tr>
<td>3</td>
<td>( V(a) \lor W(a) )</td>
<td>( K(y) ) ( \neg K(y) )</td>
</tr>
</tbody>
</table>

Inference process is also completed successfully. A decision tree consists of three levels and three vertexes (reduction in the number of vertices in 2.67 times).

Conclusions

Thus, the use of groups of defining literals in the inference methods based on the operation of the disjuncts division, can significantly reduce the amount of information processed in the process of inference, and, accordingly, reduce the requirements for the hardware resources necessary for its successful implementation [17]. In some situations, the proposed method of accelerated inference can find the solution, while its application without finding a solution could be abnormally stopped due to the exhaustion of available resources or the failure to comply on time-consuming.

It should be noted that the use of the accelerated method requires additional analysis of properties of the subject area by an expert, and also leads to an increase in the size of the knowledge base as a result of the need for metadata storage.

The proposed approach to accelerate the inference can be used in existing methods of deductive and abductive output and in newly developed methods for effective problem solving in specific subject areas: diagnosis, management, verification, forecasting, and so on [18].

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References


