Verification of Multi-Agent Systems via SDD-based Model Checking

(Extended Abstract)

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ABSTRACT

Considerable progress has been achieved in the past ten years in the symbolic verification of Multi-Agent Systems (MAS). One of the most efficient techniques put forward is based on the use of ordered binary decision diagrams (OBDDs) for representing the state space and computing the states at which specifications hold. Sentential Decision Diagrams (SDDs) have recently been put forward as an alternative symbolic representation for Boolean formulas in knowledge representation. In this abstract we report some preliminary results on the applicability of SDDs for the verification of MAS.

Categories and Subject Descriptors

D.2.4 [**Software/Program Verification**]: Model checking

General Terms

Verification

Keywords

Epistemic logic; model-checking; sentential decision diagrams

1. INTRODUCTION

Over the past 10 years a number of verification methods for MAS have been developed. A large proportion of them concerns the validation of MAS against temporal-epistemic specifications [6] so that the evolution of the agents' knowledge can be verified. The techniques put forward range from parallel approaches [10], to SAT-based techniques [13, 8], symbolic approaches [14], and symmetry reduction [2].

While recent research has enabled the verification of a wider range of systems, progress is still hampered by the so called *state explosion problem*, i.e., the fact that the model M_S to be considered grows exponentially in the number of variables used to represent S. Ordered binary decision diagrams are the de-facto standard structures for representing models symbolically. They are used by leading industrial-strength toolkits for reactive systems such as NuSMV and employed in the MAS area by MCMAS [12], MCK [7] and Verics [9]. By means of binary-decision diagrams state spaces of the region of 10^{12} are routinely verified.

Even if ordered binary decision diagrams (OBDDs) can be combined with other methodologies such as abstraction and bounded model checking, developing verification techniques on alternative, potentially more efficient, symbolic structures remains of great interest. However, finding better symbolic representations is challenging as OBDDs satisfy a number of theoretical properties that make them a very efficient data structure to represent and operate on the Boolean formulas encoding the models.

Sentential decision diagrams (SDDs) have recently been put forward [3] as an alternative to OBDDs. SDDs are more general and complex than OBDDs and they have been proven to be efficient in some areas of knowledge representation [5, 4]. This abstract reports our preliminary findings in the use of SDDs for the symbolic verification of MAS.

2. MODEL CHECKING WITH SENTENTIAL DECISION DIAGRAMS

Background. Like OBDDs, SDDs support polynomial-time Boolean operations and admit canonical representations. They have a stronger criterion for canonicity than OBDDs based on, so called, vtree structures [3]. Vtrees are full binary trees whose leaves are labelled with Boolean variables. A vtree induces the variable order defined by traversing it left-to-right; thus different vtrees may correspond to the same order. The construction of SDDs is conducted by traversing the vtree recursively from top to bottom. Therefore, right-linear vtrees, i.e., those in which every left child is a leaf, lead to SDDs which are equivalent to the OBDDs built using the corresponding variable order. However, there are SDDs that cannot be compared to any OBDD.

Model checking. In symbolic model checking we assess whether a specification ϕ is satisfied on a set of initial states I of a model M by evaluating whether $I \subseteq [\phi]_M$, where $[\phi]_M$ is the set of states on the model M where ϕ holds. Sets and functions are represented via symbolic data structures which are also used to conduct any operation required by the labelling algorithms to calculate $[\phi]_M$. A key consideration for the efficient verification of MAS via symbolic data structures lies in the definition of the heuristics for the allocation of the variables representing the state-space. Experiments have shown that in the case of OBDDs an efficient method consists of grouping variables that correspond to the same agents [12]. In the SDD-based approach here reported, we defined heuristics that extend this consideration to vtrees, thereby defining the corresponding SDDs. There

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are, however, exponentially more vtrees on n variables than the corresponding orderings for OBDDs built on them. So there are many possibilities for encoding the state-space. Furthermore, two vtrees inducing the same order may lead to sharp differences in the efficiency of the verification step. Given this, a large part of our work so far involved analysing the impact that the vtrees structures have on verification.

MCMAS-SDD. Following the considerations above, we implemented MCMAS-SDD [11], a model checker whose underlying symbolic representation is based on SDDs. MCMAS-SDD is based on the OBDD-based checker MCMAS [12], but all the verification procedures, including the computation of the set of reachable states and all the labellings, are performed on SDDs instead. MCMAS-SDD relies on the *The SDD Package* [1] as the underlying handler for all the SDD operations.

MCMAS-SDD takes as input a MAS modelled in ISPL, a modelling language based on the framework of interpreted systems [6], and a set of specifications expressed as temporal-epistemic formulas. Upon invocation, MCMAS-SDD allocates the required Boolean variables for symbolic encoding to the various agents, and builds the SDDs representing the state space, the set of states on which the specifications hold, and it establishes whether the initial states satisfy the specification in question. MCMAS-SDD includes a dedicated library for constructing vtrees based on specific variable allocations.

We have benchmarked MCMAS-SDD against several scalable scenarios and evaluated different heuristics for various classes the vtrees. At present these are generated statically based on the agent variable allocation. The most attractive results point to the adoption of agent-based grouping of variables as left branches of the vtree.

3. CONCLUSIONS

In this abstract we have introduced an SDD-based technique for the formal verification of MAS. Our design choices in the use of SDDs to represent the state space are inspired by the variable orderings adopted in OBDD-based representations. Still, since SDDs extend OBDDs, the heuristics that we implemented are more general than those present in MCMAS. The resulting toolkit, called MCMAS-SDD, is released as open-source.

We are not aware of any other model checker based on SDDs. BDD-based technology is very mature and a wide range of powerful optimisations are employed by several BDD packages. In contrast, the SDD handler we used is very recent. We expect its performance to improve considerably as the implementation becomes more mature, thereby enhancing the performance of MCMAS-SDD.

Our future work will focus on optimised representations of the state-space and on the dynamic minimisation of SDDs. In BDD-based model checking, methods for reordering variables at runtime have greatly improved the computation times. Although methods exist for dynamic restructuring of vtrees [4], these still need to be explored in order to be used efficiently in model checking.

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