

# Nonblocking Supervisory Control of State Tree Structures

Chuan Ma and W. M. Wonham, *Life Fellow, IEEE*

**Abstract**—It is well known that the nonblocking supervisory control problem is NP-hard, subject in particular to state space explosion that is exponential in the number of system components. In this paper we propose to manage complexity by organizing the system as a state tree structure (STS). STS are an adaptation of statecharts to supervisory control theory. Based on STS we present an efficient recursive symbolic algorithm that can perform nonblocking supervisory control design (in reasonable time and memory) for systems of state size  $10^{20}$  and higher. The resulting controllers are tractable and readily comprehensible.

**Index Terms**—Discrete-event systems, nonblocking supervisory control, state tree structure (STS), symbolic computation.

## I. INTRODUCTION

THE central problem of supervisory control theory (SCT) is that of optimal nonblocking supervisory control [1]. This problem is well known to be NP-hard [2]; specifically it is unlikely that any algorithm can be found to solve it that circumvents state space explosion that is exponential in the number of system components. This means that realistic industrial problems (say with state set sizes of  $10^{20}$  and higher), if formulated naively, may well exceed the computational capacity available.

It is, therefore, attractive to explore structured system architectures with the property that, if the given system can be modeled in the selected framework, the required computations can be carried out with greater efficiency than by a naive ‘monolithic’ approach. To this end, Statecharts [3] is a modeling tool which offers a compact representation of both hierarchy (vertical) and concurrency (horizontal) structure in finite state machines (FSM). Here the system state space is structured top-down into successive layers of cartesian products (AND superstates) alternating with disjoint unions (OR superstates). On this basis, Wang [4] introduced *state tree structures* (STS) consisting of a hierarchical state-space or *state tree* (ST), equipped with dynamic modules called *holons* (inspired by [5] and [6]). In [4], however, the global dynamics (semantics) of STS was not described formally and only safety specifications were considered. Furthermore, AND states had to be converted by synchronous product of factors into OR states at a higher level before computations could effectively be carried out. Unfortunately, if the root state is an AND superstate, such simple treatment of AND states

may result in the collapse of the entire hierarchy. [7] formalized Wang’s model in linguistic terms, but was similarly restricted to a purely OR state expansion.

Statecharts also underlie the *asynchronous hierarchical state machine* (AHSM) model of [8], but shared events among AND components were ruled out. An efficient algorithm was given to solve reachability problems by exploiting the hierarchical structure and asynchronism. However, [8] did not present a systematic control synthesis approach. Marchand *et al.* [9] introduced another simplified version of statecharts, *hierarchical finite state machines* (HFSM). However, HFSM ruled out shared events, were apparently restricted to be OR structures at the topmost level, and allowed only specifications of special forbidden state type.

All cited works on statecharts attempt to avoid either AND structure or shared events among components. In [10] and [11], the authors introduced a state-based STS framework that treated both AND and OR states on a more equal footing, and in AND states allowed shared events among the factors.

To design controllers for the STS framework, we exploit a well-known computational representation of state set: the *binary decision diagram* (BDD) [12], a directed graph representation of propositional logic formulas. A BDD is appealing because, for a fixed order of arguments (variables), it is a canonical form, and makes such tasks as testing for set membership or set equality highly efficient. After representing sets by BDD, the computational complexity of our synthesis is no longer polynomial in the model’s state size, but in the number of nodes in the relevant BDD. As with other approaches to solving NP-hard problems, in the worst case the number of BDD nodes ( $|nodes|$ ) grows exponentially in the number of variables and, therefore, is comparable to the number of states ( $|states|$ ) of the set it represents (see the multiplier example of [12]). However, with STS, we propose an efficient encoding scheme such that in many cases  $|nodes| \ll |states|$ . This makes the introduction of BDD into the STS framework very attractive.

In [13], Balemi *et al.* presented a BDD-based symbolic computation of the optimal (maximally permissive nonblocking) supervisor for an example of  $10^6$  states. However, computational capability was limited by the unstructured (flat) system model. Later Zhang [14] developed S(mart)TCT based on *integer decision diagrams* [15] (IDD), a BDD-like decision diagram. STCT could handle systems with more than  $10^{20}$  states. However, his work focused on a synchronous product structure with buffer-like components. In this paper, we develop a complete symbolic approach for the optimal supervisor design of STS.

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# Nonblocking Supervisory Control Of State Tree Structures

**Ali Saadatpoor**



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