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Modeling Decentralized Real-Time Control by State Space Partition of Timed Automata

Thanikesavan Sivarthi, Srivas Chennu*, Lothar Kreft
Department of Communication Networks
Hamburg University of Technology
Schwarzenberg Strasse 95, BA 4d, D - 21073, Germany
{thanikesavan.sivanthi, srivas.chennu, kreft}@tu-harburg.de

Abstract

Timed automata provide useful state machine based representations for the validation and verification of real-time control systems. This paper introduces an algorithmic methodology to translate the state space visualization of a centralized real-time control system to a decentralized one. Given a set of timed automata representing a centralized real-time control system, the algorithm partitions them into a collection of interacting submachines. Importantly, this methodology allows for model-checking of the derived decentralized system against the same set of verifications as that specified for the centralized system. The complexity analysis of the algorithm is presented as a function of the number of tasks and nodes comprising the decentralized system.

1. Introduction

Current trends in the development of microprocessor hardware, a need for lesser maintenance overheads, better scalability, and robustness are driving modern real-time control systems from centralized to decentralized architectures. Such a decentralized architecture consists of a set of loosely coupled nodes, which communicate with each other by means of a broadcast bus. Different approaches for decentralization of a centralized real-time control system have been discussed in literature [4, 6, 8, 10]. An important requirement on the process of decentralization is that the decentralized system should satisfy the same verification criteria as the centralized system. This ensures that the decentralized system provides the same functionality from the designer’s perspective. The correctness of the system can be verified by specifying the reachability, safety and liveness properties [2] that should always hold if the system has to meet its specifications.

Timed automata provide a useful state machine based representation for the validation and verification of a real-time system. The verification tools like UPPAAL [2, 3] accept such timed automata as input and perform model-checking based on a given set of verifiable properties specified by the real-time system requirements. In this paper, we detail an algorithmic methodology to perform such a verifiably correct decentralization of a centralized real-time control system. The centralized real-time control system, consisting of interdependent tasks, is modeled using timed automata and the decentralization is achieved by distributing the states of the timed automata over the processing nodes comprising the decentralized system. To our knowledge, this methodology is novel in its presentation of a consistent procedure for moving from centralized to decentralized real-time control and we expect that it will serve as a component in the process of modeling large-scale distributed real-time systems.

The rest of the paper is organized as follows. Section 2 describes the representation of a centralized real-time control system as a collection of timed automata. Section 3 describes the state space partition model of a decentralized real-time control system. Section 4 derives complexity measures for the algorithm. The paper concludes with Section 5.

2. Timed automata model of a centralized real-time control system

A centralized real-time control system consists of a set of interdependent tasks that execute concurrently, under deadline constraints, managed by a central scheduler. Each task consists of a collection of modules, which execute in a particular sequence and represent the elementary computing functions performed within the task. The flow of
control in such a system can be suitably represented by a task dependency graph, which is a directed acyclic graph \( G = (V, E) \). The vertices \( V \) of the graph represent the modules \( \{ M_k : k \in 1 \ldots N \} \) comprising the tasks, where \( N \) is the total number of modules. The edges \( E \) represent execution dependencies between these modules. Figure 1, depicts a task dependency graph for two tasks \( \{ T_i : i = 1, 2 \} \) each consisting of a set of modules. The task \( T_1 \) is comprised of five modules \( \{ M_1, M_2, M_3, M_4, M_5 \} \) and the task \( T_2 \) is comprised of three modules \( \{ M_6, M_7, M_8 \} \). For every task \( T_i \), there is an associated deadline \( d_i \) that specifies the time starting from the release time of the task within which all the modules in \( T_i \) must complete their executions. The edges of the graph represent the following possible types of dependencies between the modules:

Order dependencies are identified by solid edges, and indicate that the execution of a module depends on the completion of, or on the data from, one or more modules. In Figure 1, the module \( M_2 \) is order dependent on the module \( M_1 \).

Temporal dependencies are identified by dashed edges, and indicate that a module must finish its execution within a certain time from the completion of another module. In Figure 1, the modules \( M_5 \) and \( M_8 \) have a temporal dependency \( \Delta = 4 \), specifying that \( M_8 \) must complete within four time units of the completion of \( M_5 \).

Control dependencies are identified by dotted edges that denote mutually exclusive execution paths. The modules in an execution path can depend on other modules, except those in another mutually exclusive execution path. During runtime one of these execution paths is chosen, taking care of the dependencies along that path. In Figure 1, after \( M_3 \) completes its execution either the path with the module \( M_3 \) or the path with the module \( M_4 \) is chosen. The module \( M_5 \) is triggered after the completion of \( M_3 \) or \( M_4 \), depending on the execution path chosen during runtime.

The whole execution system represented above, consisting of the modules and the associated control flow, can be conveniently modeled by a set of timed automata. The theoretical basis for such automata has been previously developed [1] and extended [3] as a suitable means of modeling real-time systems. We base our construction and semantics of timed automata on that defined and used in UPPAAL [2], in which a timed automaton is a 6-tuple \( \langle L, L^0, C, A, E, I \rangle \) where

- \( L \) is a set of locations,
- \( L^0 \in L \) is the initial location,
- \( C \) is a set of clocks,
- \( A \) is a set of actions, and
- \( E \subseteq L \times A \times B(C) \times 2^C \times L \) is a set of transitions. An edge \( \langle l, a, \delta, \lambda, l' \rangle \) in \( E \) represents a transition from a location \( l \) to a location \( l' \) with an action \( a \). The set \( \lambda \subseteq C \) is the clocks to be reset with this transition, and \( \delta \) is a clock constraint.
- \( I : L \rightarrow B(C) \) is a function that maps the locations to the clock invariants.

Based on this definition, we construct a timed automaton (TA) denoted by \( \mathcal{A}_i \), for each task \( T_i \) in a real-time system by introducing the following abstractions:

- In a centralized real-time control system, a scheduler allocates resources and schedules the modules at times based on a scheduling mechanism. In our model, we assume a timed automaton representation of the scheduler is available and the automaton generates begin! and end! synchronization actions [2] that are sent to the timed automata representing all tasks.
- A module \( M_k \) in the task \( T_i \) corresponds to a location \( L_k \) in \( \mathcal{A}_i \). Further, when module \( M_k \) is executing \( \mathcal{A}_i \) is at \( L_k \).
- \( \mathcal{A}_i \) is initially at the location \( L^0_i \), which is defined to be the idle location. Further, whenever no module from \( T_i \) is executing, \( \mathcal{A}_i \) returns to \( L^0_i \).
- When module \( M_k \) begins its execution, \( \mathcal{A}_i \) receives the begin? synchronization action from the scheduler.

![Figure 1. A simple task dependency graph](image-url)
which also sets the variable modid to the value k. This variable ensures that only the transition to location \( L_k \) is enabled. On reception of this action, \( A_t \) moves from \( L_i^0 \) to \( L_k \), if for every module \( M_k \) that \( M_k \) depends on, the variable \( I_k \) has been set. The variable \( I_k \) is set by the scheduler when the module \( M_k \) finishes its execution.

- When the module \( M_k \) finishes its execution, \( A_t \) receives the end? synchronization action from the scheduler, which also sets the variable modid to the value k. On reception of this action, \( A_t \) moves from \( L_k \) back to \( L_i^0 \), and sets the variable \( I_k \) to indicate the completion of \( M_k \).

- In order to time the execution of the complete task, a clock \( c_i \) is associated with each \( T_i \). When the first module in \( T_i \) begins its execution, \( c_i \) is reset. When the last module in \( T_i \) completes, \( c_i \) is checked against the deadline \( d_i \).

- For the next run of \( A_t \), all the associated \( I_k \) variables are reset to their initial values.

Figure 2 and Figure 3, show the TAs constructed using the above abstractions for the tasks \( T_1 \) and \( T_2 \) in Figure 1 respectively.

![Figure 2. Timed automaton \( A_t \) for Task 1](image)

The global state of a centralized real-time system developed so far changes when at least one of the tasks changes its state. Thus the global state of the system can be viewed as a composition of the states of the individual tasks. Consequently, the problem of decentralizing this state over a collection of interconnected processing nodes can be handled on an individual task basis, adhering to the following sequence of steps:

1. The set of concurrent tasks composing the real-time system is identified.

![Figure 3. Timed automaton \( A_t \) for Task 2](image)
2. The timed automaton for every identified task is derived, as detailed in Section 2.

3. An allocation plan, which maps each module of each task to a node is obtained. This can be viewed as a combinatorial problem that involves deriving a suitable scheduling and allocation of the modules to the processing nodes, while at the same time satisfying the real-time deadline constraints. The work in [8] treats this problem as one of linear optimization, and given a task dependency graph similar to that in Figure 1, generates an optimal allocation plan and a schedule for each node, taking into consideration the completion deadlines, dependencies between modules, and allowed system utilization limits. Such a plan can also be determined by alternate methods [4, 6, 10].

4. Based on the assignment in Step 3, the TAs of the tasks are partitioned into several interacting submachines at each processing node. These timed submachines model the original system functionality by communicating with each other using broadcast messages on the bus.

5. The system bus is modeled by a timed automaton. The automaton models a queued messaging interconnect, introducing either fixed (e.g. synchronous TDMA) or variable transmission delays (e.g. CAN) [5] for the delivery of messages between the nodes.

In our model, the bus automaton \( B \) has the following locations:

1. A \textit{free} location indicating an idle bus, and an empty message queue.
2. A \textit{busy} location indicating an occupied bus, and one or more messages in the queue.

\( B \) transitions from \textit{free} to \textit{busy} on receiving the \textit{enq}? synchronization action, and adds the message to be transmitted to the queue. Whenever at the \textit{busy} location, after a delay time determined by the type of the bus being modeled, \( B \) removes a message from the queue depending on the scheduling mechanism of the bus and delivers it. If the queue is empty, it moves back to the \textit{free} location. Else, it delivers the next message to be scheduled on the bus.

State machine decomposition is an approach used in the field of digital design to minimize the area, delay, or power required, in sequential logic circuit design [7, 9]. We now detail an algorithmic approach to efficiently perform such a state machine decomposition for a given set of TAs provided as an input. The logic of the algorithm is explained below.

1. The primary inputs to the algorithm are the TAs representing the tasks constituting the centralized real-time control system and an allocation plan. This plan is assumed to be derived as described above in Step 3 of the decentralization procedure.

2. Let \( \{M_i\} \) be the set of modules, and \( \{N_j\} \) the set of nodes. Each node \( N_j \) has a scheduler, which generates \textit{begin}_j \textit{!} and \textit{end}_j \textit{!} synchronization actions, that are sent to all modules assigned to \( N_j \). Since each node scheduler works in parallel with the other node schedulers, the \textit{modid} variable cannot be global to all the schedulers. Hence, the scheduler of each node \( N_j \) has its own variable \textit{modid}_j to control the submachines running at that node.

3. The algorithm populates the submachines \( \{M_{ij}\} \), where \( M_{ij} \) represents a portion of the task \( T_i \) executing on the node \( N_j \). Each \( M_{ij} \) is initialized with an idle location \( L^0_{ij} \).

4. The algorithm analyzes the TAs given, and for each location \( L_k \) in a TA \( A_i \) assigned to \( N_j \) it creates a corresponding location \( L_k \) in the submachine \( M_{ij} \).

5. It then examines each transition in \( A_i \), and if it finds an incoming transition from \( L^0_{ij} \) to \( L_k \) it creates a corresponding transition from \( L^0_{ij} \) to \( L_k \) in \( M_{ij} \), with the following expressions [2]:

(a) The \textit{begin}? synchronization action from the original transition in \( A_i \) is copied as \textit{begin}\_j\textit{!}. This ensures the transition to location \( L_k \) is triggered only by the scheduler of node \( N_j \).

(b) In the check for the \textit{modid} variable the variable name is changed to \textit{modid}_j.

(c) Clock reset and clock constraint expressions are copied as is.

(d) For each variable \( I_{k'} \) checked for by the transition in \( A_i \), which is set by a transition from a location \( L_{k'} \) assigned to a node \( N_j' (j \neq j') \), \( I_{k'} \) is replaced with a corresponding variable \( Y_{k'} \). Otherwise, \( I_{k'} \) is copied as is.

6. If the transition in \( A_i \) is an outgoing transition from \( L_k \) to \( L^0_{ij} \), and the variable \( I_k \) set by this transition is checked for by another transition to a location \( L_{k'} \) assigned to a node \( N_j' (j \neq j') \), a committed location [2] and two transitions are created in \( M_{ij} \), as explained below:

(a) A transition from \( L_k \) to a committed location is created, with the following expressions:
i. The *end?* synchronization action from the original transition in $A_i$ is copied as $end_j?$, this ensures the transition to location $L_k$ is triggered only by the scheduler of node $N_j$.  
ii. In the check for the *modid* variable, the variable name is changed to $modid_j$. 
iii. Clock reset and clock constraint expressions are copied as is. 
iv. The assignment to set the variable $I_k$ is copied as is. 

(b) A transition from the committed location to $L^0_{i,j}$ is created. A synchronization action $enql$ is added to the transition, and the variable $msgid$ is set to the value $k$. This action is sent to the bus automaton $B$. The bus automaton reacts to the $enql$ synchronization action by adding the message to be delivered to its queue, and eventually setting the corresponding variable $Y_k$ after a delay determined by the type of the bus being modeled. 

7. On the other hand, if the transition in $A_i$ is an outgoing transition from $L_k$ to $L^0_{i,j}$ and the variable $I_k$ set by this transition is not checked for by any other transition, a transition from $L_k$ to the initial location $L^1_{i,j}$ is created with the following expressions:

(a) The *end?* synchronization action from the original transition in $A_i$ is copied as $end_j?$.
(b) In the check for the *modid* variable, the variable name is changed to $modid_j$.
(c) Clock reset and clock constraint expressions are copied as is.
(d) The assignment to set the variable $I_k$ is copied as is.

It is important to note that the algorithm assumes that the clocks used in the decentralized system are global [2] to all automata and that the read and write operations to these clocks can be performed in a synchronous, consistent manner.

The state partition algorithm detailed thus is now applied to partition the TAs in Figures 2 and 3, from our example in Figure 1. Let us assume that the decentralized system consists of two processing nodes $N_1$ and $N_2$, which are connected by a FIFO broadcast bus. We provide the following inputs to the algorithm:

1. The TAs representing the tasks $T_1$ and $T_2$.
2. An allocation plan which maps the modules $M_1$, $M_2$, $M_3$, $M_6$ and $M_7$ to the node $N_1$, and the modules $M_4$, $M_5$ and $M_8$ to the node $N_2$.

The algorithm generates four partitioned submachines $M_{1i}$, $M_{12}$, $M_{21}$ and $M_{22}$ as shown in Figures 5, 6, 7, and 8 respectively.

The FIFO bus is modeled by the timed automaton shown in Figure 4. The automaton maintains a circular buffer of length $len$, with two pointers $front$ and $back$ which point to the first and last message in the queue respectively. These pointers are updated whenever a message is added or removed from the queue, taking care of the boundary conditions of an empty or a full queue. The clock $c_d$ tracks the fulfillment of the message transmission delay $t_{rd}$.
machines in combination with the bus automaton representing the decentralized system can be confirmed in UPPAAL, by verifying that the relevant reachability, safety and liveness properties identified for the centralized case continue to hold for the decentralized case. Thus the decentralized model provides a verifiably correct decentralization of the given centralized system.

4. Complexity analysis

We now present a brief analysis of the time and space complexity of the state partition algorithm presented in Section 3. This analysis provides an important insight into the processing requirements of the algorithm.

In order to calculate the complexity measures of the algorithm, we first define the following execution parameters:

- $n$ is the number of tasks in the real-time system being modeled.
- $m$ is the number of processing nodes.
- $p$ is the maximum number of elementary modules in a task.
- $k$ is the maximum number of elementary modules of a task assigned to a node.
- $l$ is the maximum number of variables of the type $L_r$ associated with the incoming transition to a location.

4.1. Time Complexity

An expression for the time complexity of the algorithm is derived from the following observations:

- Each location in a TA representing each task is processed once. This processing has a complexity of $O(n \cdot p)$. For each such location, the incoming and outgoing transitions associated with it are examined.

  - Each variable checked for by the incoming transition is examined. The complexity of this processing is approximately $O(l)$.
  
  - For each variable set by the outgoing transition from the location, the algorithm verifies whether it is checked for by an incoming transition to a location on a different node. The complexity of this processing is $O(n \cdot p \cdot l)$.

Combining the above, we conclude that the time complexity of the algorithm is $O(n \cdot p \cdot l + m \cdot n \cdot k \cdot l)$.

4.2. Space Complexity

The approximate space complexity of the state partition algorithm, calculated by a reasoning similar to that for ascertaining time complexity, is $O(n \cdot p \cdot l + m \cdot n \cdot k \cdot l)$, and stems from the following facts:

- The storage requirement for the TAs grows as $O(n \cdot p \cdot l)$. 

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Figure 6. Submachine $M_{12}$

Figure 7. Submachine $M_{21}$

Figure 8. Submachine $M_{22}$
The storage requirement for the submachines grows as \( O(m \cdot n \cdot k \cdot l) \).

Combining the two measures, we arrive at the space complexity measure given above.

In practice, an efficient implementation of the algorithm can mitigate the above complexity estimates, by means of well-designed data structures that support efficient search and update operations. Further, in case of a real-time control system consisting of a large number of concurrent tasks, both time and space complexity of the model can be significantly reduced by considering separately the operation of the system in different functional modes, where a mode is a clearly distinguishable operational phase of the system. This is because not all tasks in the system are required in all of these functional modes, i.e. certain tasks may be exclusive to one mode of operation. This approach would provide a suitable means for managing the potential state space explosion problem that could occur when modeling large real-time control systems.

5. Conclusion

In this paper we have discussed a state space partition methodology for verifying the decentralization of a centralized real-time control system. The timed automata modeling a centralized system are partitioned into a collection of interacting submachines running on the different nodes of a decentralized system. Further, the process of decentralization also models an automaton for the bus and the message transmission delays therein. The distributed submachines, along with the bus automaton, provide a verifiably correct decentralization of the given centralized system. When integrated into an overall system design, the state partition algorithm would serve as a base for better visualization of the dynamics of the decentralized system, and provide for validation and verification of the decentralized real-time architecture, and its reaction to failures, both of the processing nodes, and of the bus.

References