A Genetic Algorithm Based Approach for Event Synchronization Analysis in Real-time Embedded Systems

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Abstract

In real-time embedded systems, due to race conditions, synchronization order between events may be different from one execution to another. This behavior is permissible as in concurrent systems, but should be fully analyzed to ensure the correctness of the system. In this paper, a new intelligent method is presented to analyze event synchronization sequence in embedded systems. Our goal is to identify the feasible sequence, and to determine timing parameters that lead to these sequences. Our approach adopts timed event automata (*TEA*) to model the targeted embedded system and use a race condition graph (*RCG*) to specify event synchronization sequence (*SYN-Spec*). A genetic algorithm working with simulation is used to analyze the timing parameters in the target model and to verify whether a defined *SYN-Spec* is satisfied or not. A case study shows that the method proposed is able to find potential execution sequences according to the event synchronization orders.

Keywords *– embedded system, event, synchronization sequence, timed event model, race condition, genetic algorithm.*

1 Introduction

Real-time embedded systems are computing systems that must react within precise time constraints to current events in the application environment. A reaction that occurs late could not only be useless but also catastrophic. A real-time system must have some notion of time. The time base can be absolute, corresponding to a physical clock, or relative, based on specific events. A synchronization primitive can be implemented to establish and maintain ordered execution between computational tasks [1]. However, because of race conditions [2], which are caused due to the non-determinism in the inter-tasks communication and synchronization mechanisms, the order that the synchronization operations take place may be different from on execution to another. This can result in different order of concurrent operations which may lead to incorrect behavior and output. Even if the orders of concurrent operations are permissible, they should be analyzed thoroughly to ensure the correctness of the systems [1].

Concurrent tasks in real-time embedded systems usually communicate through message queues or shared variables. Enforced by RTOS, the operations on message queues are atomic. Similarly the accesses to shared variables should be guarded by semaphores. However, multiple accesses to message queues or shared variables may be interleaved in arbitrary orders. This leads to the so called message races [3] and semaphore races [4]. Figure 1. shows an example of a semaphore race where tasks 1 and 2 can take the semaphore in distinct orders in different execution scenarios.

In the past two decades, many static and dynamic approaches [3], [4], [5], [6] are proposed to detect race conditions in concurrent programs. However, the problem of detecting all feasible race conditions is NP-hard in general cases [2]. Due to the scheduling and timing characteristics in real-time embedded systems, many race conditions detected by those approaches may be infeasible in practice. For instance, in the example of Figure 1. , if we assume the system uses priority-based preemption scheduling algorithm, the priority of Task 1 is higher than Task 2 and they are released at the same instant, then the execution sequence (1) would always happen, while the execution sequence (2) would never happen. So, in order to ensure the correctness of real-time embedded systems, it is necessary to know exactly whether a race condition is feasible or not, i.e., whether a specific case of synchronization order of some potential events can happen in an execution. If so, it is necessary to find a corresponding execution sequence which satisfies the case for understanding, analysis and testing.

To find the possible execution sequences, we can consider a parametric analysis about the timing instants that tasks are released and external events occur. Such an analysis is not only time consuming, but also have to face the exponential increase of state spaces in the execution model. In this paper, a new method, based on a genetic algorithm, is presented to analyze event synchronization in real-time embedded systems. There are several contributions of this method:

1. Timed event automata (*TEA*) are presented to describe the timing behavior of a target real-time system, and each state in the *TEA* is a synchronization event.
2. A race condition graph (*RCG*) [17] is used to specify the synchronization order of events which have races.
3. A genetic algorithm (*GA*) working with a simulation-based approach [14], [15] is used to verify whether the

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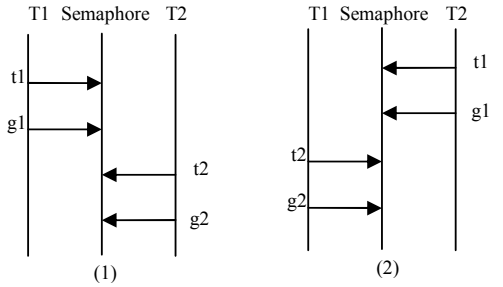
events synchronization order specified (*SYN-Spec*) is satisfied or not by the target *TEA*; if it is satisfied, a corresponding execution sequence is given.

Binary Semaphore s = available;

Task 1	Task 2
……	……
semTake(*s*);	*semTake*(*s*);
//Access the critical resource	//Access the critical resource
semGive(*s*);	*semGive*(*s*);
……	……

(*a*) A program with two tasks



(*b*) Two execution sequences with different event synchronization orders

Figure 1. An example of semaphore race

The rest of the paper is organized as follows. In Section 2, some related works are given. Section 3 presents the real-time system modeling and simulation with *TEA*. Section 4 describes how to use *RCG* to specify the events synchronization order. In Section 5, a *GA* is presented to working with simulation approach to analyze the timing parameters. Then, a case study of real-time dining philosopher program is shown up, followed by a conclusion and the future work.

2 Related Works

A well-known approach which can be used to analyze and verify the real-time embedded systems is model checking technology. In this approach, a system is represented by a kind of formal model based on finite state machine, such as timed automata [7], timed I/O automata [8], and linear hybrid automata [9] and so on. Properties required are specified by a kind of temporal logic language, such as LTL, CTL, and TCTL [10], or even by another formal model. The algorithms for model checking are typically based on an exhaustive state space search of the model of the target system: for each state of the model it is checked whether it behaves correctly, that is, whether the state satisfies the desired specification. In its most simple form, this technique is known as reachability analysis. The disadvantage of model checking technology is the state explosion problem. So, its capacity is restricted by the huge program state spaces.

Perry [11] described a system that automatically detects races in a parallel program. In this approach, the dynamic execution trace of the program was used to build a task graph and logged points of event style synchronization. David [12] developed a static analysis method for determining which dependences in a program cannot possibly result in a data race because of schedule restrictions enforced by event posts and waits. Fumihiko [13] presented a new parallel computational model, the LogGPS model, which was useful to analyze synchronization costs of parallel programs that used message passing. All these approaches do not consider scheduling and timing, so they cannot be used for checking the feasibility of a race in real-time system.

Johan and Anders [14], [15] presented a simulation-based approach to do the impact analysis of real-time system. In their approach, a simulation model of a target system, which is described by ART-ML, is extracted from both static and dynamic analysis. Though it was only used for timing analysis, the simulation-based approach can be used to do much further analysis of real-time systems.

In our previous work, we have proposed a technology based on model checking to verify race conditions in real-time embedded systems [16], and a race condition graph to analyze the concurrent program behavior is presented in [17]. In this paper, we propose a new method to analyze the event synchronization order based on simulation-based technology according to race conditions in the target systems.

3 Embedded System Modeling And Simulation

The analysis approach for event synchronization order is shown in Figure 2. . There are two inputs to the analysis: a target system which is represented as *TEA* and a specific synchronization order *SYN-Spec* which is described by *RCG*. Then, an execution algorithm is used to simulate the target *TEA* based on a priority-based preemptive scheduling algorithm, inter-task synchronization and communication constructs and virtual clock. At last, *GA* working with simulation is used to analyze the timing parameters in the *TEA* to verify whether the *SYN-Spec* is satisfied or not. If the *SYN-Spec* is satisfied, a corresponding execution sequence is obtained.

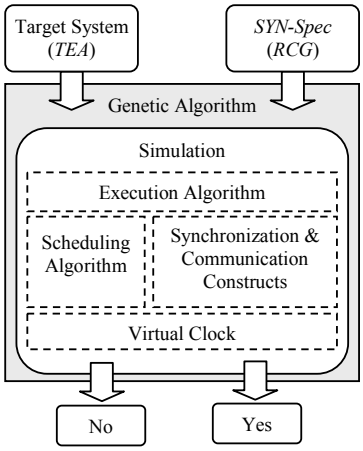


Figure 2. Architecture of the method

3.1 Syntax and Semantics of TEA

A real-time system is composed of multiple concurrent tasks with a scheduling algorithm to control

CPU resource. These tasks synchronize and communicate with each other by using message passing, shared variables, etc. In this paper, timed event automata (*TEA)* are used to describe the timing behaviors of a real-time system. It includes synchronization events (*SYN-Event*), such as sending message (*MS*), receiving message (*MR*), taking semaphore (*ST*), giving semaphore (*SG*) and task delay (*TD*) and so on.

Definition 1: *SYN-Event*. Each *SYN-Event* e in a real-time embedded system is defined as a 5-tuple $e =< p, \lambda, o, x, i >$, where p is the calling task; λ maps e into one of the following types: *MS*, *MR*, *ST*, *SG*, *TD*; o is the operating object of e, which may be a message queue, a semaphore or even null; x is the related data of e, which may be a string, an integer, a parameter or even null; i is an unique identifier of e. The relation of λ , o and x is shown in TABLE I. .

TABLE I. Synchronization Events

Event type (λ)	Operating Object (o)	Related Variable (x)
MS	Message Queue	Data Sent
MR	Message Queue	Data Received
SG	Semaphore	Null
ST	Semaphore	Null
TD	Null	Delay Time

In this paper, we focus on the synchronization and communication constructs with FIFO queues of asynchronous message passing, binary semaphore and counting semaphore, but other synchronization events can also be added according to the requirement of cases.

Definition 2: *TEA*. A real-time embedded system is described as a *TEA* which is a 7-tuple: $S =< P, X, E, A, \tau, \mu, \gamma >$ with the following restrictions. P is a set of tasks; $\forall p \in P$ is a periodic or an aperiodic task, including task name, task ID, task priority, and entry and exit nodes. X is a set of variables which may be integer variables (*int*), timing parameters (*para*), message queues (*mq*), binary semaphores (*bs*) or counting semaphores (*cs*). E is a set of *SYN-Events*. $A \subseteq E \times E$ is a set of transitions. $\forall a(e_s, e_t) \in A$, such that

- $\tau(a)$ is a timing predicate describing the effective execution time and timing constraint from a source event e_s to a target event e_t of a, and τ (a) ::= [x] | [x] [y, z] | [x] [y, +∞], where $x \in R^+ \wedge y \in R^+ \wedge z \in R^+ \wedge z \geq y$, [$x$] is the effective execution time, and [y, z] is a timing constraint.
- $\mu(a)$ is a local predicate describing the triggering condition of a, and μ (a)::= *true* | $(x \sim n)$ | $(x \sim y)$ | $\neg\mu$ | ($\mu_1 \wedge \mu_2$), where x and y are variables; $n \in R^+$; $\sim \in \{ \leq , < , = , \; !=, \; > , \geq \}$; $\neg$ and $\wedge$ are Boolean negation and disjunction respectively. If μ (a)::= *true*, it is usually omitted.
- $\gamma(a)$ is a set of assignments. If τ $(a) \wedge \mu$ (a) = *true*, the transition a is triggered, and then γ (a) is executed. The syntax of γ (a) is: $\gamma(a) ::= L := R \mid (\gamma_1 \vee \gamma_2)$, and $L ::= x$ and $R ::= n \mid x \mid (x \sim y) \mid (x \sim n)$, where x and y are variables, $n \in R^+$; $\sim \in$ { +, − , *, /}.

3.2 *Simulating the TEA*

The simulator engine is based on four parts: scheduler, synchronization & communication constructs, virtual clock and execution algorithm. Let $S =< P, X, E, A, \tau, \mu, \gamma >$ be a *TEA*, $\forall p \in P$ has three states: *ready*, *run*, *wait*. A priority-based preemptive scheduling algorithm [20] is used to schedule the tasks and control the states transitions of tasks. With the synchronization & communication constructs which include message-passing, semaphore and task delay, $\forall e \in E$ is processed according to the characteristic of each type of *SYN-Events* during an execution.

For timing-accurate simulation, *TEA* uses timing predicate τ to describe the amount of CPU time required by a task to execute from one *SYN-Event* to the next, i.e. the execution time of the code between these model events. In this simulation approach, a virtual clock C is used to calculate the execution time of *TEA*. When an execution is started, C is increased steadily until the execution is ended. Let $a_i(e_i , e_{i+1}) \in A$ be a transition, and $\tau(a_i) = [t_e(a_i)][min(a_i), max(a_i)]$ be a timing predicate of a_i, then the algorithm for time consume from e_i to e_{i+1} is shown in Figure 3. . In this algorithm, the function of *getGlobalClockValue*() is used to read the value of virtual clock *C*.

```
Process timeConsume (Transition a)                    (1)
    t = te(ai);                                       (2)
    cc = getGlobalClockValue();                       (3)
    pc = cc;                                          (4)
    while (pc − cc) < t, do                           (5)
        pc = getGlobalClockValue();                   (6)
    end while                                         (8)
End process                                           (9)
```

Figure 3. An algorithm for time consume

In a simulation, all tasks in *TEA* are concurrent tasks and the execution algorithm of each task is shown in Figure 4. . In this algorithm, statement (2) means a task executes from a "*start*" node; statement (5) searches for the next transition a according to e_s and the corresponding local predicates; statement (6) calls *timeConsume()* function to consume execution time from current event to the next event; statement (7) is used to do a set of assignments; statement (8) gets the next event and statement (9) uses *executeEvent*() to execute the event according to the event type. Note that an executing task may be preempted at any time by the other ready task with higher priority.

```
Process taskExecution                                 (1)
    es = "start";                                     (2)
    et = null;                                        (3)
    while not et = "end", do                          (4)
        a = getNextTransition(es);                    (5)
```

```
        timeConsume(a);                          (6)
        executeAssignment( γ (a));               (7)
        e_t = getNextEvent(a);                   (8)
        executeEvent(e_t);                       (9)
        e_s = e_t;                               (10)
    end while                                    (11)
End process                                      (12)
```

Figure 4. An execution algorithm of each task in *TEA*

Let $t_o(a_i)$ be the total time spent on the transition a_i, we have $t_o(a_i) = t_e(a_i) + t_d(a_i) + t_b(a_i)$, such that:

- $t_e(a_i)$ is the effective execution time of a_i. It is the time spent executing run-time or system services on its behalf, without being pended or delayed.
- $t_d(a_i)$ is the sleeping time of a_i. It is caused by a task delay event *TD*.
- $t_b(a_i)$ is the time spent by a_i blocked due to the unavailability of a resource, such CPU, semaphore, or message.

Therefore, a feasible execution of *TEA* should satisfy the following inequality: $\forall\ a_i \in A$, $min(a_i) \le t_o(a_i) \le max(a_i)$.

Figure 5. (a) and (b) show a simple example of *TEA*. It includes two tasks T1 and T2, and the priority of T1 is higher than T2. In these two tasks, there are timing constraints between e_1 and e_2, x and y are two timing parameters.

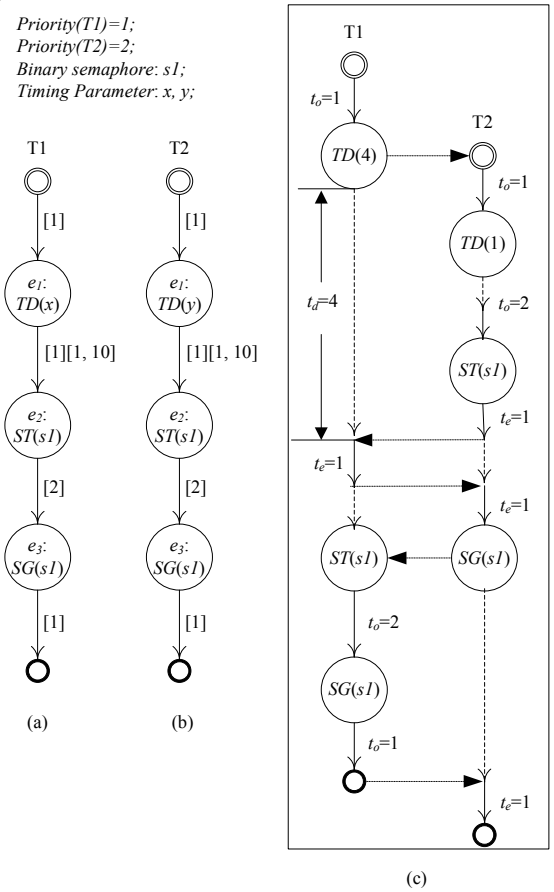


Figure 5. Examples of a timed event model and an potential execution sequence

Assume the timing parameters x and y equal to 4 and 1, Figure 5. (c) is an execution of the *TEA*. First, T1 is selected to run by the scheduler as it has a highest priority in all ready tasks; e_1 of T1 is a task delay event which makes it to sleep for 4 time units, then the scheduler picks up T2 to run. The event e_1 of T2 is also a task delay event which makes it to sleep for 1 time units, and T2 goes on executing after waking up. Because the execution time from e_1 to e_2 in T2 is 1 time unit, the total time spent on the first transition of T2 is 2 time units. During the transition from e_2 to e_3 in T2, T1 wakes up, so T2 is preempted by T1 which has a higher priority. When T1 is going to simulate e_2, which is a taking semaphore event, it is blocked because the semaphore has been taken by T2, so context switches to T2 again. After T2 gives the semaphore by e_3, it is preempted by T1 because the semaphore is ready now. Finally, T1 finishes firstly and T2 finishes later. In this simulation, the time spent on the transition from e_1 to e_2 in T1 is t_o = 4 + 1 + 1 = 6, while the time spent on the transition from e_2 to e_3 in T2 is t_o = 1 + 1 + 1 = 3, so the execution satisfies the timing constraints of the *TEA*, i.e., the execution is feasible. In Section 5, we will use a *GA* to generate the values of timing parameters according to the *SYN-Spec*.

4 Specification Of Event Synchronization Order

An execution of *TEA* exercises a sequence of synchronization events. Let $S =< P, X, E, A, \tau, \mu, \gamma >$ be *TEA*, an execution sequence generated by a simulation is denoted as: $Q = \{<t, e> \mid t \in R^+$ is the happened time of $e, e \in E\}$. There are two characteristics of Q:

- Q satisfies *happened-before* relation, denoted as "$\xrightarrow{HB}$", which is a partial order over the *SYN-Events* and shows the sequence of events that potentially affect one another [19].
- Q has a synchronization order, which is a total order over all of the *SYN-Events* of an execution.

With a postmortem approach [3], an execution sequence is analyzed to detect race conditions. In this section, *RCG* is used to specify the synchronization order of *SYN-Events* which have races.

4.1 ***Race Set***

Let Q be an execution sequence. A race set of Q is given as a triple $RS = < E_R, \xrightarrow{HB}, \xrightarrow{RD} >$, where E_R is a finite set of events and $E_R \subseteq E$ and $\xrightarrow{HB}$ and $\xrightarrow{RD}$ are relations defined over E_R.

The race related events in the set of E_R, are the events that have direct relationship with race conditions in Q. The *race-dependence* relation, denoted by $\xrightarrow{RD}$, shows the relative order in which events execute and the race dependence with each other. In this paper, we focus on message races and semaphore races. Assume there are 3 events *a, b, c*$\in E$, i.e., *a*, *b* and *c* are events in the

SYN-sequence Q:

- Assume a and b are sending message events, c is the receive message event, and there is a message race between events a, b with respect to c, i.e., c may receive the message from a first in one execution or even receive the message from b first in another execution. If a comes before b in the Q, then $a \xrightarrow{RD} b$, otherwise, $b \xrightarrow{RD} a$.
- Assume a and b are taking semaphore events, and there is a semaphore race between events a and b, i.e., event a may take the semaphore firstly in one execution or b may take the semaphore firstly in another execution. If a comes before b in the Q, then $a \xrightarrow{RD} b$, otherwise, $b \xrightarrow{RD} a$.

4.2 Race Condition Graph

Let $RS = < E_R, \xrightarrow{HB}, \xrightarrow{RD} >$ be a race set of an execution sequence Q. An *RCG* is a graph $G = <V, L>$, where $V = E_R$ is the set of vertices of the graph G and $L \subseteq V^2$ is the set of relations of V. There are two kinds of L in an *RCG*:

1) If events $a \in E_R$, $b \in E_R$ and $a \xrightarrow{HB} b$, a solid arrow "$\longrightarrow$" is used to show their *happened-before* relation in the *RS*.
2) If events $a \in E_R$, $b \in E_R$ and $a \xrightarrow{RD} b$, a dashed arrow "- - ->" is used to show their *race-dependence* relation in the *RS*.

The *SYN-Spec*, i.e., the synchronization order of *SYN-Events*, can be described by an *RCG*. For example, Figure 6. shows a *SYN-Spec* of the dining philosopher case (which will be introduced in Section 6).

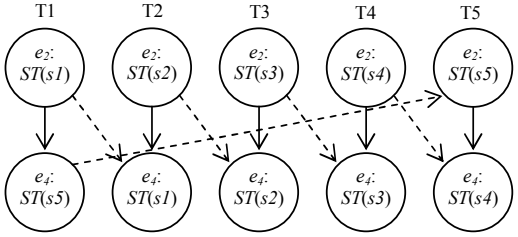


Figure 6. An example of *SYN-Spec*

In this *SYN-Spec*, there are 5 tasks (T1, T2, …, T5), 5 binary semaphores (*s1*, *s2*, …, *s5*), and 10 *ST* events. Assume the notation $\lambda(p, i, o)$ denotes the i^{th} *SYN-event* in the task p operating on the object o, the corresponding race set of this example is shown in Figure 7. .

$RS = \{ ST(T1, 2, s1) \xrightarrow{HB} ST(T1, 4, s5);$
$ST(T2, 2, s2) \xrightarrow{HB} ST(T2, 4, s1);$
$ST(T3, 2, s3) \xrightarrow{HB} ST(T3, 4, s2);$
$ST(T4, 2, s4) \xrightarrow{HB} ST(T4, 4, s3);$
$ST(T5, 2, s5) \xrightarrow{HB} ST(T5, 4, s4);$
$ST(T1, 2, s1) \xrightarrow{RD} ST(T2, 4, s1);$
$ST(T2, 2, s2) \xrightarrow{RD} ST(T3, 4, s2);$
$ST(T3, 2, s3) \xrightarrow{RD} ST(T4, 4, s3);$
$ST(T4, 2, s4) \xrightarrow{RD} ST(T5, 4, s4);$
$ST(T1, 4, s5) \xrightarrow{RD} ST(T5, 2, s5)\};$

Figure 7. The corresponding race set of the example

Let $G=<V, L>$ be an *RCG* with respect to an execution sequence Q, and $G'=<V', L'>$ be a *SYN-Spec*. If every vertex $v \in V'$ also belongs to V and every edge $l \in L'$ also belongs to L, i.e., G' belongs to G, denoted by $G' \subseteq G$, then we say that Q satisfies the *SYN-Spec* G', denoted by $Q \models G'$.

Proposition. A real-time system S described by *TEA* satisfies a *SYN-Spec* G described by *RCG*, if and only if there is at least one execution sequence Q obtained by simulating *TEA* and $Q \models G$.

5 Genetic Algorithm Based Approach for Parametric Analysis

Because of the non-determinacy of real-time embedded systems, there usually have some parameters unknown which influence the timing of the execution. In this paper, a *GA* based approach is used to search heuristically these timing parameters in a *TEA*. The goal of the analysis is to identify a set of timing parameters that result in a specific *SYN-Spec*. If no such timing parameters can be found, we can conclude that the *SYN-Spec* is not a valid one.

5.1 Chromosome Encoding

Assume there are n timing parameters in the *TEA*. In the *GA* approach, each timing parameter x_i ($i \le n$) is represented as a binary string with the length of L_i, which is decided by the range and precision of x_i. A chromosome is composed of a set of binary strings, which is shown in Figure 8. .

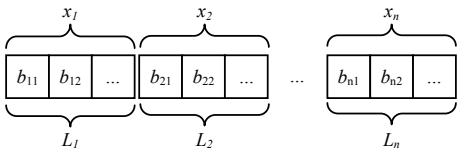


Figure 8. A chromosome encoding

5.2 Fitness Function

The fitness function gives a quantitative measure of the suitability of the generated timing parameters for the purpose of satisfying the *SYN-Spec*. Let $G'=<V', L'>$ be a *SYN-Spec*. According to the proposition mentioned in Section 4.2, if the *TEA* satisfies G', then there is a new *RCG* $G=<V, L>$ derived from a new execution sequence obtained by simulating the *TEA*, and $G' \subseteq G$. Therefore, in this paper the fitness function is used to measure the similarity of G' and G, i.e., the similarity of two *RCGs*.

In order to know the similarity of two *RCGs*, it needs to calculate the difference between them. Figure 9. shows an algorithm to calculate the difference between a *SYN-Spec* G' and an *RCG* G derived from a new execution sequence obtained by simulating the target

TEA. The statement (1) initializes a variable named *difference*. For each edge *l'*=<*v'*, *u'*> from *G'*, the statement (3) aims to find the same vertices *v* and *u* in *G* according to the SYN-event information described by *v'* and *u'*. If it fails to find *v* or *u* in *G*, then we say that the difference between *G* and *G'* is infinity. The statement (4) and (5) show that if the synchronization relation between *v* and *u* isn't the same as *v'* and *u'*, then the *difference* is increased.

```
Process calculateDifference (G', G)
// G' = <V', L' > is a SYN-Spec of the TEA;
// G = <V, L > is an RCG derived from an new
// execution sequence of the TEA;
set the difference = 0 initially;                    (1)
for each edge l'=<v', u' > ∈ L'                      (2)
   get the vertices v = v' and u = u' from V;        (3)
   if the synchronization relation between v and u   (4)
isn't the same as l', then
      difference = difference + 1;                   (5)
   end if                                            (6)
loop                                                 (7)
return difference;                                   (8)
End process
```

Figure 9. An algorithm of calculating the difference between two RCGs.

Therefore, in the *GA*, the fitness of a chromosome (i.e., a set of timing parameters) is dominated by the difference value calculated using the algorithm shown in Figure 9. : if the difference value between the *SYN-Spec G'* and a new *RCG G* becomes smaller, then *G'* becomes more similar with *G*, i.e., the corresponding chromosome has higher contribution and suitability; if the difference value equals to 0, then $G' \subseteq G$, i.e., the *SYN-Spec* is satisfied by the target *TEA*.

5.3 ***Termination Condition***

The genetic algorithm is terminated at the following conditions: (1) it has successfully found a group of timing parameters with which an execution sequence generated by simulating the target *TEA* satisfies with the *SYN-Spec*; (2) the number of generations exceeds the upper limit and the genetic algorithm is terminated, at the situation we consider that the target model does not satisfy the *SYN-Spec*.

5.4 ***Analysis Process***

Let $S =< P, X, E, A, \tau, \mu, \gamma >$ be *TEA* and *M* is a set of timing parameters. The process of analysis is described in Figure 10. .

Step 1: Initialization.
Generate a set of initial chromosomes randomly.

Step 2: Calculate fitness.

```
for each chromosome, do
   decode it and get a set of values X;
   substitute X for M in S;
   simulate S and get a new execution sequence Q;
   if all timing constraints is satisfied in Q, then
      generate a new RCG G from Q';
      if G' ⊆ G, then
         output the Q and X;
         return success;
      else
         calculate the difference between G' and G';
      end if
   else
      continue;
   end if
loop
```

Step 3: Genetic operations.
Select one or two chromosome(s) from the population with a probability based on fitness to participate in genetic operations: selection, crossover, and mutation. Renew individual chromosome(s) with specified probabilities based on the fitness.

Step 4: Termination.
If the number of generations exceeds the upper limit specified, then return fail; else go to step 2.

Figure 10. Analysis process of the GA

Specially, if a chromosome cause deadlock during a simulation, the algorithm will mutate the chromosome and repeat the simulation again and again until the system runs smoothly.

6 A Case Study

As a case study, a real-time dining philosopher program, which is implemented on the VxWorks RTOS, is used for the case study. There are 5 dining philosophers with the same priorities: T1, T2, T3, T4 and T5. 5 chopsticks are represented by 5 binary semaphores *s1*, *s2*, *s3*, *s4*, and *s5*. To eat their dinner, T1 takes *s1* and *s5*, T2 takes *s2* and *s1*, T3 takes *s3* and *s2*, T4 takes *s4* and *s3*, T5 takes *s5* and *s4*. Thus, there have 5 semaphore races in the program. In addition, to represent a possible thinking time before picking up a chopstick, there is a task delay event for random time before each semaphore taking operation. So, there are 10 timing parameters in the system: *x1*, *x2*,…,*x10*. In the study, we assume that for each timing parameter *x1*, there has $1s \le x1 \le 8s$; the timing constraint between each task delay event and semaphore taking event is [1, +∞].

Figure 11. shows the T1 described by *TEA*, the effective execution time of each transition is calculated from traces of original executions on the VxWorks OS and a target processor board. The time unit is second. Other tasks are described by *TEA* similarly. The static data of the case is shown in TABLE II. .

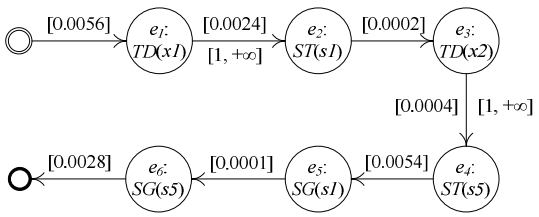
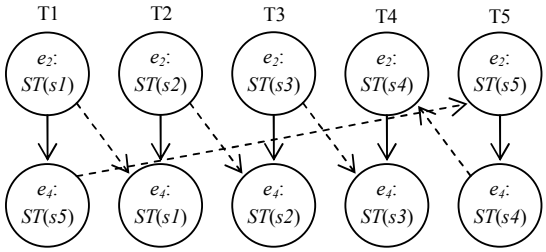


Figure 11. T1 described by TEA

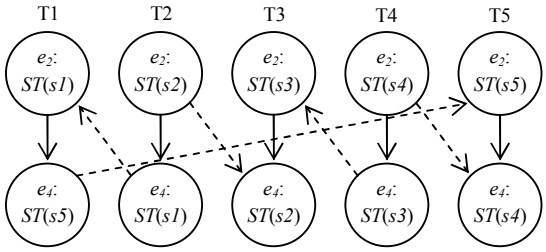
TABLE II. Static Data of the case study

Items	Number
Processes	5
Events	35
Transitions	40
Variables	15
Parameters	10

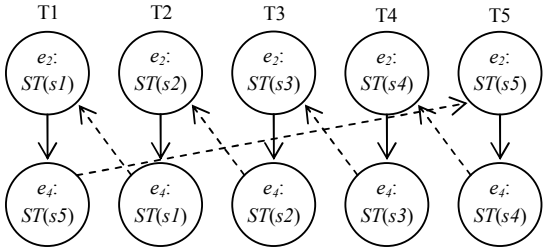
Figure 12. shows 4 *SYN-Specs* described by *RCGs*, which mean the different orders of taking chopsticks of 5 dining philosophers. For example, in *SYN-Spec* 1, T1 takes *s1* before T2, T2 takes *s2* before T3, T3 takes *s3* before T4, while T5 takes *s4* before T4 and T1 takes *s5* before T5. The purpose of the case study is to verify whether these event synchronization orders are possible or not.



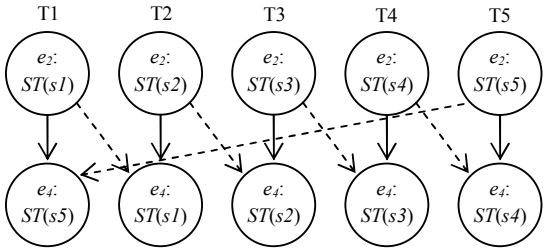
(1) *SYN-Spec* 1



(2) *SYN-Spec* 2



(3) *SYN-Spec* 3



(4) *SYN-Spec* 4

Figure 12. Specifications of events synchronization

In this case study, the crossover rate of *GA* based approach is 0.7, the mutation rate of *GA* is 0.001, the revision rate is 0.5 and the number of initial population of chromosomes is 6. After simulating the target *TEA*, the result is shown in the TABLE III. . The result shows that *SYN-Spec* 1 and 2 are satisfied by the *TEA* but *SYN-Spec* 3 and 4 are not. *SYN-Spec* 3 is infeasible because a global circle is included in *SYN-Spec* 3 [17], while the *SYN-Spec* 4 causes a deadlock and the event e_4 (take the 2nd chopstick) can never succeed.

TABLE III. Result of the case study

SYN-Spec No.	Result	Generations of GA	Values of Timing Parameters
1	Yes	61	*x1*=1, *x2*=1, *x3*=5, *x4*=8, *x5*=2, *x6*=5, *x7*=7, *x8*=1, *x9*=3, *x10*=3
2	Yes	578	*x1*=1, *x2*=1, *x3*=7, *x4*=7, *x5*=8, *x6*=1, *x7*=6, *x8*=1, *x9*=3, *x10*=2
3	No	*Inf*	*None*
4	No	*Inf*	*None*

7 Conclusion

In this paper, a simulation-based analysis with *GA* based search is presented to analyze event synchronization in real-time embedded systems. The *TEA* presented is composed of *SYN-Events* but not system states. Instead of using reachability analysis, the target *TEA* is simulated to generate execution sequences. Via analyzing execution sequences with a postmortem method, it is able to check whether a *SYN-Spec* described by *RCG* is satisfied or not. In the mean time, a *GA* based approach is used to analyze timing parameters in the target *TEA*. Experiments show that the method proposed can be used to find execution sequences according to the event synchronization order defined by user. As a consequence, the execution sequence defined by *SYN-Spec* can be indentified. Also, test sequences can be generated to verify the system operations.

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