OFF-LINE SCHEDULING OF REAL TIME APPLICATIONS WITH VARIABLE DURATION TASKS.

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Abstract: We propose a model oriented scheduling methodology for highly coupled real time applications. We show that variations in the computation times of tasks may hazard the safeness of the controlled process. For the sake of reliability we take conditional instructions of tasks' code explicitly into account, in order to reduce the potential failures. We fisrt adapt the task's temporal model to this context, then we model applications using autonomous Petri nets which run under the earliest firing rule with terminal marking set. We define two concepts of schedulability: the local schedulability and the global one and we define the concept of scheduling graph. Finally, we show how to obtain a scheduling graph from the graph of global schedulability.

Keywords: off-line scheduling, Petri Nets, conditional instructions, scheduling graph.

1. INTRODUCTION

A constantly increasing number of either autonomous or assisted processes (cars, nuclear power station, plane, space probe) are controlled by real time systems interacting with their own environment. Yet these systems are not safe from failures that may put human beings' lives in danger or jeopardize substantial economic value. That is why, it is necessary to develop methods to minimize those risks by validating the real time applications that control the processes. In most cases, the failures come from disregarded temporal constraints. Indeed, a real time application is defined as a multitask application in which each task is subjected to the inherent temporal constraints of the controlled processes. Thus, the main problem will be to choose a scheduling policy which would distribute each active job of task on the processor(s) so that the temporal constraints are respected. Two techniques can achieve that. The first one consists in executing a scheduling algorithm, which aim is to define at every moment the task to execute: it is the online scheduling. The second one consists in a previous analysis of the application and of the computation of valid schedules of the task executions within a temporal window of suitable size. Whatever the method, the schedulability analysis relies on a temporal model of the task (Liu and Layland, 1973; Stankovic *et al.*, 1998) allowing to represent each task by its temporal constraints: R_i, the date of the first activation, D_i the relative deadline of the execution of the task, T_i the period and C_i the computation time of the task calculated on the target hardware. Many works have made validation tools achievable by relying on heterogeneous scheduling contexts: hard and soft temporal constraints, the presence

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of real time primitives (resources and synchronizations which make the scheduling problem NP-Hard (Dertouzos and Mok, Dec. 1989), the reduction of response time, of jitter etc). Yet, a very few tools are actually used or usable in the industrial world. Indeed, the inaccuracy of execution time due to both the task's code itself and the processor that executes it, questions the relevance of the classic tools of schedulability analysis. It is the reason why we propose an off-line schedulability analysis methodology that takes the fluctuations of duration of tasks into account by relying on works that deal with the determination of the worst case of execution times. For that purpose, we have to extend the temporal model of Liu Layland in order to take the variations coming from the conditional instructions of the tasks (an important cause of variation) into account. We used the modeling of real time application by Petri nets (Choquet-Geniet *et al.*, 1996; Grolleau and Geniet, 2000) to analyze the feasibility of highly coupled applications (i.e. applications with a lots of resources and synchronizations) , then we show how to describe valid behaviors of the application, by means of scheduling graphs and finally, we explain how to get those graphs from the analysis of the Petri Net.

In a first part, we look into the difficulties of computation time estimation and the scheduling problems that it generates. Then in a second part, we introduce a new temporal model of task which takes the conditional instructions of the code into account and we reformulate the scheduling problem according to this new context. In a third part, we present the modeling of the application by autonomous colored Petri nets under the earliest firing rule and we show how to extract a scheduling graph describing a feasible behavior of the application.

2. SCHEDULING INSTABILITY PHENOMENA

In most real time applications, to find out a scheduling policy respecting constraints of the system proves to be a major issue. As an answer to that problem, we generally rely on a temporal model (Liu and Layland, 1973) that describes the temporal constraints of each task of the application in order to find and then validate a scheduling policy. But among the parameters that model a task, the execution time is probably the most complex to estimate. Those durations enable us to quantify the time allotted to the CPU to process each job of the tasks. It is thus an upper bound which is reckoned up from the task's program code and the features of the hardware. Each tool of scheduling analysis being based on a pattern of the tasks, that upper bound (Worst Case Execution Time) represents then an input data whose accuracy of estimation will determine the quality of the scheduling policy's validation. Therefore, researches on the WCET must take the two following preconditions into account (Puschner and Koza, 1989). First, the reckoned WCET must be safe, ie. it has to be an upper bound whatever the execution context may be. Second, the estimation of WCET has to be as accurate as possible or instability phenomena may occur as shown in figure 1: the reduction of the duration of one of the job of the task can cause a temporal fault in spite of the validation of the scheduling policy (Deadline Monotonic[3]). This kind of instability phenomena had been highlighted by (Graham, 1969).

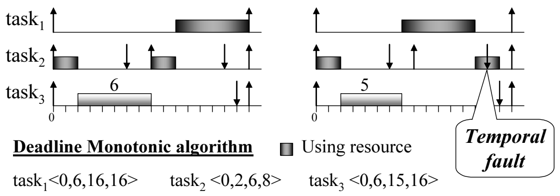


Fig. 1. An example of a scheduling failure due to a computation time reduction. If task 3 has an effective computation time equal to 5 instead of 6, task 1 can get the resource at time 7 before task 2 is released, causing task 2 to miss its deadline.

However the current methods of calculation of WCET do not all take the importance of real time primitives into account. In a context of highly coupled application, the traditional estimation of the WCET does not always correspond to the paths of execution where all the real time primitives are activated. However, as far as the analysis of schedulability is concerned, it is necessary to consider all the real time primitives that can occur. Consequently it is essential to consider the estimation of the WCET, to which should be added every real time primitive that can be activated in the various paths of the execution of the task. It seems then obvious that the resulting temporal model will be strongly over constrained what reduces the number of potential scheduling and complicates validation. To overcome that problem we suggest a method that allows to take the various paths of execution of a same task into account in order to isolate each real time primitive. Thus a task will be modeled for the analysis of schedulability by a set of execution paths. The existence of these paths is partly due to the different forms of conditional instructions present in the source code. That is why we propose to extend the temporal model of Liu Layland in

[3] DM (Deadline Monotonic) refers to the priority allocation algorithm: the task with the shortest deadline (the smallest value of D) is assigned the highest priority.

order to explicitly consider the IF THEN ELSE relevant instructions that is to say those which make it possible to isolate temporal primitives or sufficiently different execution times. Thereafter we will more specifically study the influence of the conditional tests on the schedulability analysis while considering that the methods of WCET analysis allow to obtain our model of conditional task.

3. CONDITIONAL TASKS AND SCHEDULING

3.1 The extended temporal model

We consider real time applications compounded of synchronous periodic tasks ($r_i = 0$). However let's point out that our method can take asynchronous periodic tasks into account, but it does at the cost of a combinatory explosion as far as the accessibility graph construction and the scheduling graph extraction are concerned. Optimization criteria need to be found to solve the problem.

Our objective is to refine the functional block description in order to take conditional instructions into account, which requires to modify the temporal model of tasks. We extend the Liu-Layland model in order to describe all the durations of the conditional branches: a task is represented by three deterministic parameters (the date of the first release, the relative deadline and the period) and by a *multiset E* of durations, each one corresponding to a possible behavior of the task. This new pattern of tasks is very close to the multiframe model of (Mok and Chen, 1996). However, unlike the later, we don't need the knowledge of the series of execution time for each task since each job of task may be processed with whatever execution time of the multiset. Let us note that if there is no conditionals instruction, the multiset E contains a single duration, which corresponds to the usual model.

In this temporal model, we have left the association between the real time primitives and the execution times aside. However, this information is not lost since it will be entirely integrated in the modeling of the application by Petri nets.

3.2 Scheduling graph

Considering on line scheduling strategies, the presence of conditional instructions matters only for the application validation, but most of these on line algorithms can be used without any adaptation even when conditional instructions are involved. On the contrary, off line scheduling strategies must be adapted. Indeed, if we consider tasks without conditional statements (durations are deterministic), the objective of an off line scheduling strategy is to build one or more valid schedules. This cannot be used if conditional statement are involved, because the various choices in conditional instructions will induce different behaviors of the application, which could not be described in a single schedule. In order to describe the behavior of a conditional application, we introduce scheduling graphs: a scheduling graph is a graph where each branch corresponds to a schedule of the application obtained by considering for each task only one of their paths. We call *split sub-application* each of these applications.

We then reformulate the scheduling problem, and define two concepts of schedulability:

- An application is said to be *locally schedulable* if each of its split sub-application is schedulable, i.e. there is for each one of them a valid schedule,
- An application is said to be *globally schedulable* if there is at least one valid scheduling graph, i.e. all deadlines are met whatever the conditional choices.

A globally schedulable application is obviously locally schedulable (but the converse does not hold if the application uses real time primitives). This comes from the fact that each branch of a scheduling graph is a valid schedule for one split sub-application.

4. MODELLING BY MEANS OF PETRI NETS

The schedulability analysis methodology which we proposed relies on (Choquet-Geniet *et al.*, 1996; Grolleau and Geniet, 2000; Grolleau, 1999). It consists in modeling the application by a constrained marking colored Petri nets, under the earliest firing rule with terminal marking set. The feasible schedules are then obtained through the construction of the state graph. The model includes two parts: the task system which is obtained through a classical modeling of the functional description of the application, and a clock system which models time (see figure 2). We have adopted a discrete modeling of time (Kopetz, 1992; Fohler, 1994): an external clock (RTC) counts the time in each place Time$_i$, which acts as a local clock used to release periodically the related tasks. Let us note that each transition corresponds to an action of duration one time unit, and that all transitions of the task system are in competition for obtaining the processor. It follows that, according to the earliest firing rule, at each time, one single valid transition is fired.

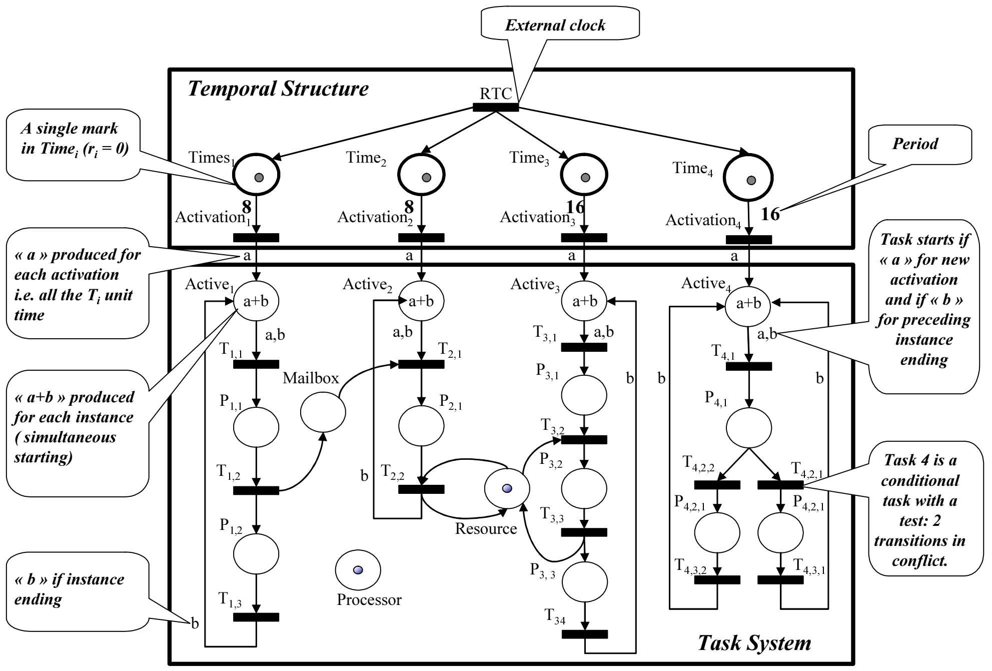

External clock
Temporal Structure
RTC
A single mark in $Time_i$ ($r_i = 0$)
Period
« a » produced for each activation i.e. all the T_i unit time
Task starts if « a » for new activation and if « b » for preceding instance ending
« a+b » produced for each instance (simultaneous starting)
Task 4 is a conditional task with a test: 2 transitions in conflict.
« b » if instance ending
Mailbox
Resource
Processor
Task System

Fig. 2. Petri Nets model for an application of 4 tasks with a conditional task. The links toward processor are not shown.

It results that only conservative schedules[4] can be produced. But for the sake of scheduling power since there is no optimal conservative scheduling algorithm in a scheduling context with resource and synchronization, we need also to consider non work conserving schedules. For that purpose, we introduce in the task system a further task, called idle task, which models the inactivity of the processor. When transitions of this task fire, the processor remains idle what allows to produce non work conserving schedules too. The computation time of the idle task is P(1-U) [5]. Morever, the knowledge of the number of idle times during the metaperiod P help us for the detection of temporal fault during marking graph construction. When conditional tasks are involved, the utilization factor U is no more deterministic and the duration of the idle task becomes variable too. In order to match the previously used rule (a transition of the task system fires each unit time), we have adapted our model so that the duration of the idle task could be dynamically modified during the simulation of the Petri Nets. To allow these time units exchanges, the idle task is represented by a special place, holding as many tokens as idle time has been assumed within the metaperiod. For that purpose, we have chosen a method which has the advantage to minimize the number of backtracking operations during the construction of the accessibility graph. It consists in assuming

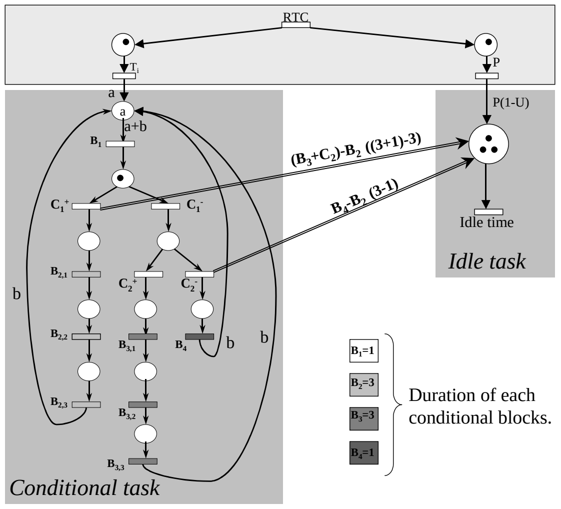


Fig. 3. Idle time exchange between the Idle task and a Conditional task with maximal duration policy. The multiset of the Conditional task is E={6,7,5}, so the number of token of the Idle task is calculated with max(E)=7. Each computation of the Conditional task with a different duration increases the number of idle times.

that the maximal durations are always chosen within the multiset. Consequently, the duration of the idle task is assumed to be minimal. When a conditional task is computed, if the conditional test doesn't correspond to the maximum execution path, the duration of the idle task has to be increased of the difference between the worst and effective duration (cf. figure 3).

[4] in a conservative (or work-conserving) schedule, a task never intentionally waits
[5] where U is the processor utilization factor of the application and P is the LCM of the periods of the tasks

5. OFF-LINE ANALYSIS

5.1 Construction of global accessibility graph

Once the model constructed, we are interested in its exploitation in order to obtain valid scheduling graphs. From this Petri net, we only need to build a P depth final marking graph since the application is cyclic with a period of P (metaperiod). This means that, we have the same states at a t-depth and at t+k×P (k>0) in the marking graph. We then remove from the marking graph all states without successor, of depth less than P. They correspond to states of the application where fatal scheduling decisions have been made: temporal faults can no more be avoided. We call *accessibility graph* the reduced graph which contains only valid states. This graph contains all the possible valid schedules for the different splitted sub-applications. It can thus be used for studying the local schedulability. For the sake of global schedulability, the graph must be further reduced; indeed, we must insure that at each node, when a edge labelled by one alternative of the conditional statement exists, the edge labelled by the other alternative exists too. This means at a given depth in the graph, if there is a conditional test then it must exist a succesion of states until the depth P, corresponding to the metaperiod of the application, independently of the positive or negative result of the test. In this case only, the global schedulability is considered and scheduling graphs can be extracted. In order to purge the marking graph from lonely alternative paths, the basic idea is that each time, a choice is made of a path in a task, the choice of the other path corresponding to the other alternative in the conditional instruction, must be possible. Else, the first path must be removed. This operation can be made directly during the construction of the accessibility graph if we chose the construction in depth methods. The resulting graph is then called a *global accessibility graph.*

5.2 Extraction of a scheduling graph

The last step of the analysis consists then in the extraction of the scheduling graphs. The main difficulty is to deal with the size of the scheduling graph which depends on the number of the possible execution paths of the tasks.

Property: We consider n tasks defined by $< r_i, E_i, D_i, T_i >$ for $1 < i < n$, which do not use real time primitives, so:

- The number of possibles behaviors in a scheduling graph is $\prod_{i=1}^{n} (\#E_i)^{\frac{P}{T_i}}$,
- The global accessibility graph which contains all of the possible scheduling graphs is entirely hold in a hyper-cube which has $\sum_{i=1}^{n}(\Phi(E_i)) + 1$ dimensions,

# represents the number of elements of the multiset E_i,

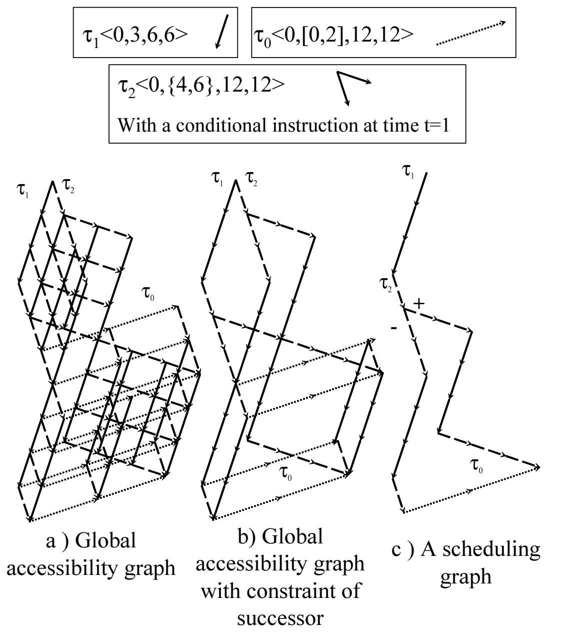
$\Phi(E_i)$ is the maximum number of interleave conditional tests from all the behaviors of the task i.

Nevertheless, we can note that in the case of highly coupled applications, the size of the graph decreases significantly. For a better result, we can choose to act in two ways. First, when we build the global accessibility graph, we can apply some constraints like successor constraints or define a threshold for jitter or response time for a task or a set of tasks (Grolleau, 1999). These kind of criterion are called *a priori constraints* and allow us to reduce the size of the global accessibility graph which is the most important drawback of our method. The second method is used to choose from this reduced graph a optimized scheduling graph with some precise criterion : the better response time, the minimum jitter...(cf. figure 4). Anyway, both methods must be refined in the case of conditional task. When a task could have several behaviors, we can choose for example to only take into account the best response time for all of the different behaviours or at the opposite the worse. The result will be surely different. By default, we have choosen to consider the most pessimistic way for all the criterion.

Now that we can schedule periodic tasks with variable duration and by that way control the number of idle time in a scheduling graph, we have the possibility to optimize their position in the schedule. In the case some aperiodic tasks occur, we can look into the positionning of each idle time to simulate the on-line algorithms like Polling Server, Deferrable Server, Priority Exchange (Lehoczky *et al.*, 1987)... It can be made by a special criteria that uses a weighting function (like sinusoidal function with a period equal to the period of the simulated server). It forces each idle time to occur periodically and then may reduce their response time. We can then extract scheduling graphs that can be used for mixed scheduler in the case of both periodic and aperiodic tasks occurrences.

6. CONCLUSION

We have proposed a method for scheduling analysis of highly coupled real time applications which uses a Petri net modeling. We have shown that the variations of execution time have to be taken into account. Indeed, the use of the WCET does not give inevitably good results. The indeterminism of the current processors, the use of the optimized



τ_1<0,3,6,6>
τ_0<0,[0,2],12,12>
τ_2<0,{4,6},12,12>
With a conditional instruction at time t=1
τ_1
τ_2
τ_0
+
-
a) Global accessibility graph
b) Global accessibility graph with constraint of successor
c) A scheduling graph

Fig. 4. (a) The global d'accessibilit graph; (b) a reduce graph with constraint of successor; (c) a scheduling graph which is extract from b .

compilers, the programming with particular instructions which increases the number of different behaviors from each task, makes it impossible to get an exact measurement of the execution times (Puschner, 2002). In spite of these difficulties, the analysis of WCET and schedulability strongly interests industrialists (Nielsen *et al.*, 2002). It is the reason why we have to try to benefit from works on the WCET to integrate in our method the relevant conditional instructions that can be found in the code of tasks. After extending the temporal model of (Liu and Layland, 1973) to conditional tasks, we have defined two concepts of schedulability, coming directly from the implications of conditional tasks: local and global schedulability. We have shown that there is no equivalence between both. In addition, we have adopted the concept of idle task, because the duration of this task is closely related to the duration fluctuations of the application tasks. We have proposed a modeling of the idle task that allows on one hand a production of non work conserving schedules and on the other an optimization in the construction of the marked graph (the idle task enables to considerably reduce the number of non valid states). We have shown how to extract a scheduling graph with some optimization criteria for response time or jitter minimizing. The next step of this work is to extend our method to sporadic tasks, induced by conditional blocks within which new tasks are requested. Our method must be adapted in order to take into account this new kind of tasks model. Our goal is then, thanks to efficient idle time managing, to define a mixed scheduler for both periodic and sporadic tasks.

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