Real-time Reconfigurable Scheduling of Aperiodic OS Tasks on Multiprocessor Systems

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Abstract: The paper deals with the real-time scheduling of aperiodic OS tasks that composed multiprocessor embedded systems which can change their behaviors at run-time for each reconfiguration scenario. A reconfiguration scenario is assumed to be any run-time automatic addition, removal, or also update of OS tasks according to external events or also user requirements. We propose a new approach to check the system’s feasibility of the tasks while minimizing their response times. An agent-based architecture is proposed to provide run-time technical solutions for users in order to reach again the system’s feasibility after any reconfiguration scenario for the whole multiprocessor embedded systems. We discuss the paper’s contribution by analyzing the experimental results that we did on a running example.

1 INTRODUCTION

This paper deals with the problem of hard scheduling of both periodic, sporadic and aperiodic tasks on multiprocessor real-time embedded systems in a critical real-time environment. In this work, we introduce an efficient scheduling algorithm to optimize the response time of the multiprocessors embedded system at run-time while ensuring that all periodic tasks meet their deadlines and to accept as many sporadic tasks, which can be guaranteed to meet their deadlines after a reconfiguration scenario \( \psi_h \) (\( h \in 1..M \)) was applied. This efficient algorithm results in the dynamic scheduling solutions. These solutions are presented by a proposed intelligent agent-based architecture where a software agent is used to evaluate the response time, to calculate the processor utilization factor and also to verify the satisfaction of real-time deadlines. The agent dynamically provides technical solutions for users where the system becomes unfeasible (e.g. deadlines are violated). The organization of this paper is as follows. Section 2 presents the reconfiguration of tasks in the case of a multiprocessor embedded systems and presents our new contribution and our proposed algorithm for optimal scheduling theory. Section 3 discusses experimental results of the proposed approaches research. Section 4 summarizes the main results and presents the conclusion of the proposed approaches.

2 RECONFIGURATION OF MULTIPROCESSOR REAL-TIME EMBEDDED SYSTEMS

Multiprocessor architectures provide a rich computing environment from which a wide range of problem domains, including real-time applications can benefit. Efficient and effective scheduling techniques have been made in the literature (Gharbi et al., 2010). The major scheduling problem which has been more addressed is that of assigning a set of tasks to different processors in the system, in order to minimize the total response time of the total task set. Indeed, scheduling algorithms for multiprocessor architectures, including those for real-time applications can be divided into two main categories of static and dynamic scheduling. In static scheduling, the allocation of tasks to the processors is determined off-line prior to the start of task execution. In contrast, dynamic scheduling algorithms perform assigning tasks and processors allocation on-line in order to use more
comprehensive and up-to-date knowledge of the tasks and the environment (architecture).

In recent real-time systems also, computation model has become more and more complex and embedded systems must operate in dynamic environments where human activities occur at any moment, then some tasks, such as emergency task, external event task, human interaction task (add, removal, update), etc., arrive aperiodically and for this reason a reconfiguration scenario ψh must be done at run-time to adapt the whole system to its environment and to handle all the user requirements.

The goal of our original approach dealing with the reconfiguration and scheduling of real-time systems is to construct systems that are guaranteed to meet all hard deadlines and that minimize the response time for all soft deadlines (Khalgui, 2010). This a challenge that has frequently not been met to our knowledge and that we aim to meet in this work. Indeed, to obtain this goal, this system should be changed and automatically adapted to its environment on the occurrence of random disturbances such as hardware-software faults. A random disturbance is defined in this work as any random internal or external event allowing additions, removals or updates of tasks at run-time to adapt the system’s behavior. Nevertheless, when an automatic reconfiguration scenario ψh is applied, the deadlines of new and old tasks can be violated. We mean by reconfiguration scenario ψh in this work, the removal, update or addition of new tasks when they arrive at run-time without prior knowledge in order to save the whole system when random disturbances happen at run-time. We define an agent-based architecture that checks the system’s evolution and defines useful solutions for users when deadlines are not satisfied after any reconfiguration scenario ψh. Two cases of suggestions are possible to be provided by our intelligent agent: modification of worst case execution times of tasks and the migration of some tasks from the corresponding processors to others that belongs to the inclusion set. We need by inclusion set in our work, the set of processors in which the tasks can be scheduled after any reconfiguration scenario ψh when a migration request has done and in this case all the relevant state information of that migration is transferred to the new processor. Otherwise, it is called exclusion set. The users should choose one of these solutions to re-obtain the system’s feasibility and to minimize the response time of the soft tasks. We developed a tool RT-Reconfiguration and tested it in order to support the agent’s services.

As well as we know, our approach is among the first and best solutions which consists in assigning the periodic tasks to the various processors for each reconfiguration scenario ψh is that we propose in this original work. It implies a large number of advantages, in particular to avoid the complexity of multiprocessor scheduling systems, and our proposed intelligent agent try to achieve this objective by focusing on evenly balancing the load among the processors and on reducing response times of the total task set.

2.1 Approach Description

To explain our approach well, we assume that there are K identical processors numbered from 1 to K, and m real-time tasks numbered from 1 to m that composed a feasible subset of tasks entitled ξold and need to be scheduled. At time t and before the application of the reconfiguration scenario ψh, each one of the tasks of ξold is feasible, e.g. the execution of each instance in each processor is finished before the corresponding deadline and the tasks are not assumed to be arranged in any specific order.

Each processor p assigns a set of periodic tasks TS p = {τ1,p, τ2,p,...,τk,p}. This allocation is made with an allowance algorithm at the time of the design. These tasks are independent and can be interrupted at any time. Each task τi,p has an execution time (Worst Case Execution Time) C_i,p, one period T_i,p, a deadline D_i,p which is assumed to be less than or equal to its period, e.g. D_i,p ≤ T_i,p. Each task instance k has to respect its absolute deadline, namely the kth authority of the task τi,p, named τi,p,k which must be completed before time D_i,p,k = (k-1)T_i,p + D_i,p. Each processor p will execute its local tasks by using EDF, it means that the priorities p_i,k of periodic tasks are dynamic and the scheduler guarantees that every instance of every task will run before its deadline. These tasks are handled by a global scheduler (GS), which assigns them to processors by using the state information of the local schedulers. Moreover, under EDF scheduling, a task will fit on a processor as long as the total utilization of all tasks assigned to that processor does not exceed unity (the total utilization factor = 1). Finally, for reasons of simplicity, we assume that all the overheads of context exchange, scheduling of tasks, the preemption of the tasks and the migration cost of the tasks are equal to zero.

We assume now the arrival at run-time of a second subset ξnew which is composed of n real-time tasks at time t (t1 = t + Δt). We have a system CurrentSys(t1) composed of m + n tasks. In this case a reconfiguration scenario ψh is applied. The reconfiguration of the system Sysψh means the modification of its implementation that will be as follows at time t1:

\[ ξψh = CurrentSys(t1) = ξψh_{new} ∪ ξψh_{old} \]
If the reconfiguration scenario $\psi_h$ is satisfied:

Using EDF. So, according to (Mok, 1983), the follow-

Let $\psi$ each reconfiguration scenario

multiple of periods for each reconfiguration scenario

$LCM$ $\psi$

When the reconfiguration scenario $\psi_h$ is applied, two cases exist:

- If tasks of $\xi_{old} = \xi_{new} \cup \xi_{old}$ are feasible, then no
  reaction should be done by the agent

- Otherwise, the agent should provide different solu-
  tions for users in order to re-obtain the system’s
  feasibility. We define the following such services

First Step

the agent tries to modify the execution times of tasks

Iterative Second Step

the agent tries to consider old tasks of $\xi_{old}$ as new

Third Step

the agent tries to migrate some tasks of $\xi_{new} = \psi_{new} \cup \xi_{old}$ from their current processors to be scheduled in

other ones which belong to their inclusion group. The

inclusion group of each task is formed by a group of

processors in which this task can be scheduled. When

a task can’t be scheduled in a list of processors, this

group is called exclusion group. This technique is

applied in the migration scenario $\psi_h$.

2.2 Feasibility Analysis for Tasks

By considering real-time tasks, the schedulability analysis should be done in each processor in an appropriate

Hyper-Period. According to (Brocal V., 2011), a hyper-period is defined as $HP = [\xi, 2 \ast LCM + \xi]$, where

$LCM$ is the well-known Least Common Multiple

of periods for each reconfiguration scenario $\psi_h$ of all the tasks that composed the system $\xi_{new} \psi_h$ and

($\xi_{old} \psi_h$) is the largest task offset of all tasks $\xi_{old} \psi_h$ for each reconfiguration scenario $\psi_h$ on each processor $p$.

Let $m + n$ be the number of tasks respectively in $\xi_{old}$ and $\xi_{new}$. By assuming an unfeasible system at time

$t_1$, and each processor $p$ will execute its local tasks by

using EDF. So, according to (Mok, 1983), the following

formula is satisfied:

$$\sum_{i=1}^{m+n} \frac{C_i^p \psi_h}{T_i^p} \text{ should be } > K, \text{ where } K \text{ is the number of}\n$$

identical processors.

Our proposed algorithm provides guarantees for both old and new tasks in each processor $p$ if and only if,

$$\sum_{i=1}^{m+n} \frac{C_i^p \psi_h}{T_i^p} + \sum_{i=n+1}^{m+n} \frac{C_i^p \psi_h}{T_i^p} \leq 1$$

where

$\sum_{i=1}^{m+n} \frac{C_i^p \psi_h}{T_i^p}$ denotes the sum of utilization factor of $n_1$ old tasks in the processor $p$ for each reconfiguration

scenario $\psi_h$ and,

$\sum_{i=n+1}^{m+n} \frac{C_i^p \psi_h}{T_i^p}$ denotes the sum of utilization factor of new arrival $n_2$ tasks in the processor $p$ for each re-

configuration scenario $\psi_h$.

2.3 Contribution: Agent-based

Real-time Reconfigurable Model

Our main contribution is the efficient schedu-

lability algorithm of multiprocessor real-time

tasks implementing reconfigurable multiprocessor

embedded systems. By applying a preemptive

scheduling, the assumed system is characterized

by tasks such that each one is defined by a tuple

$(S_i; C_i; D_i; T_i; inclusion; exclusion)$. A system is called

asynchronous, if its tasks have offsets and are not

simultaneously ready. Note that in synchronous

systems, all offsets are zero (all tasks are released at

time $t = 0$).

Formalization

We propose for each reconfiguration scenario $\psi_h$ a

new expression for the hyper-period $hp$ in the

processor $p$ by $HP = [\xi, 2 \ast LCM + \xi]$. Let $n_1^{p, \psi_h}$

$n_2^{p, \psi_h}$ be the number of periodic tasks in

$Current_i^{p, \psi_h}(t)$ for each reconfiguration scenario $\psi_h$.

2.3.1 Agent’s Principal

Let $\Gamma^p_{\psi_h}$ be the set of all possible tasks that can

implement the system in the processor $p$ for each

reconfiguration scenario $\psi_h$, and let us denote by

$Current_i^{p, \psi_h}(t)$ the current set of periodic tasks im-

plementing the system at time $t$. By considering a

feasible system $\Gamma^p$ before the application of the re-

configuration scenario $\psi_h$, each one of the tasks of

$\xi_{old} \psi_h$ is feasible, e.g. the execution of each instance

is finished before the corresponding deadline. In this

case, we note that $Feasibility(Current_i^{p}(t)) \equiv True$. An

embedded system can be dynamically reconfig-

ured at run-time by changing its implementation to

delete old or to add new real-time tasks. We denote in

this research by $\xi_{new}$ a list of new tasks to be added to

$Current_i^{p}(t)$ after a particular reconfiguration scenario

$\psi_h$. In this case, the intelligent agent should check the
system’s feasibility that can be affected when tasks violate corresponding deadlines, and should be able to propose technical solutions for users.

Now, we apply at time $t$ a dynamic reconfiguration scenario $\psi_b$ in order to adapt the system’s behavior to guarantee the system’s feasibility which depends on two major goals of the reconfiguration: Consequently, the task $\tau_k^{\psi_h}$ can violate also its relative (corresponding) deadline and all the system $\text{Current}_P^{\psi_h}(t)$ will be unfeasible at time $t$. In this case the following formula is satisfied for each reconfiguration scenario $\psi_h$:

$$\sum_{i=1}^{n^P_{\psi_h}} C_i^{\psi_h} = \min \left( \sum_{i=1}^{n^P_{\psi_h}} D_i^{\psi_h} \right) > 1$$

- The first major goal to control the problem's complexity is to minimize the response time of tasks of $\text{Current}_P^{\psi_h}(t) = \xi_{\text{new}}^{\psi_h} \cup \xi_{\text{old}}^{\psi_h}$, then the agent will not modify the $\xi_{\text{old}}$ tasks and should provide different solutions for users by reconfiguring only $\xi_{\text{new}}^{\psi_h}$ which is composed by $n^P_{\psi_h}$ tasks in order to satisfy functional requirements.
- The second major goal of obtaining the system’s feasibility is to meet deadlines of periodic tasks. Then, the agent should react by updating the global system $\text{Current}_P^{\psi_h}(t) = \xi_{\text{new}}^{\psi_h} \cup \xi_{\text{old}}^{\psi_h}$ which is composed by $n^P_{\psi_h}$ and $n^P_{\psi_h}$ periodic tasks in order to re-obtain the system’s feasibility and provides different solutions for users.

### 2.3.2 Meeting Deadlines of Periodic Tasks

#### Solution 1: Modification of Worst Case Execution Times

The agent proceeds as a first solution to modify the Worst Case Execution Times (WCET) of tasks of $\xi_{\text{new}}^{\psi_h}$ and $\xi_{\text{old}}^{\psi_h}$ in the processor $p$ for each reconfiguration scenario $\psi_h$. To obtain a feasible system, the following formula should be satisfied:

$$\sum_{i=1}^{n^P_{\psi_h}} C_i^{\psi_h} = \min \left( \sum_{i=1}^{n^P_{\psi_h}} D_i^{\psi_h} \right) + \sum_{i=1}^{n^P_{\psi_h}} \alpha_i^{\psi_h} = 1$$

- Based on the Layland J. (1973) theorem.

$$\sum_{i=1}^{n^P_{\psi_h}} C_i^{\psi_h} = \min \left( \sum_{i=1}^{n^P_{\psi_h}} D_i^{\psi_h} \right) + \sum_{i=1}^{n^P_{\psi_h}} \alpha_i^{\psi_h} = 1$$

where $\alpha_i^{\psi_h}$ represents the extra processing time required by each task to meet its deadline. The new WCET of $\Gamma^{\psi_h}$ tasks in the processor $p$ for each reconfiguration scenario $\psi_h$ is therefore deduced from $\gamma_j^{\psi_h}$. The new WCET of $\Gamma^{\psi_h}$ tasks in the processor $p$ for each reconfiguration scenario $\psi_h$ is therefore deduced from $\gamma_j^{\psi_h}$.

#### Solution 2: Migration of Tasks

The agent proceeds now as a second solution to migrate some tasks of $\xi_{\text{new}}^{\psi_h}$ and $\xi_{\text{old}}^{\psi_h}$ in the processor $p$ for each reconfiguration scenario $\psi_h$. Indeed, the agent is responsible for allocating the tasks to the $K$ computing processors in a good way. In order to react to varying run-time conditions, the system feasibility requires homogeneous task migration capabilities. Run-time task migration can be defined as the relocation of an executing task from its current location, the source processor $i$, to a new location, the destination processor $j$ ($i \neq j$; $i,j = 1...K$). This allows the OS to e.g. minimize energy savings and response time of the whole system. It also enables processors management by moving tasks away from processors with a high amount of workload or which have their utilization factors $> 1$. In order to relocate a task, the intelligent agent notifies the task by means of a migration request signal$^{(1)}$. Whenever that signaled task reaches a migration point (MP), it checks if there is a pending migration request or the destination processor $j$ belongs to the exclusion group of the current migrated task for each reconfiguration scenario $\psi_h$. In such case of these two reasons, the relevant state information of that migration point is transferred to the intelligent agent$^{(2)}$. Consequently, the intelligent agent will instantiate the same task on a...
different processor. The new task instantiation will be initialized by using the state information previously captured by the intelligent agent\(^3\). Finally, the task resumes execution at the corresponding migration point (MP).

One of the main issues in homogeneous (we suppose before that all the processors are identical) task migration is the overhead incurred by checking for a pending migration request during normal execution (i.e. when there is no pending migration request).

Especially since a task requires frequent migration points in order to reduce the reaction time. The reaction time (Figure 1) is the time elapsed between selecting a task for migration and the selected task reaching the next migration point. In order to minimize the checking overhead during normal execution, further denoted as migration initiation, we propose a novel technique for the new generation of embedded systems. This technique uses the inclusion and exclusion groups information of each task for each reconfiguration scenario \(\psi_h\) in order to reduce the area search feasibility of such systems and to minimize the reaction time and consequently the response time will be minimized too.

**Final Conclusion.**

In conclusion, we can deduce that by arrival of \(\xi_{\text{new}}\) tasks at run-time, the following formula is satisfied for each reconfiguration scenario \(\psi_h\):

\[
\sum_{i=1}^{(m+n)\psi_h} \frac{C_{\tau_i}}{T_{\tau_i}} > K, \text{ where } K \text{ is the number of identical processors.}
\]

Then, after the reconfiguration scenario \(\psi_h\) was applied at run-time to the whole system by the intelligent agent, our proposed algorithm provides guarantees to both old and new tasks if and only if, we have in each processor \(p\) for each reconfiguration scenario \(\psi_h\):

\[
\sum_{i=1}^{(m+n)\psi_{new}} \frac{C_{\tau_i}}{T_{\tau_i}} \leq 1, \text{ in each processor } p \text{ for each reconfiguration scenario } \psi_{new}, \text{ (sufficient condition).}
\]

Moreover, we have calculated \(K_{\psi_{new}}(p,\psi_{new}) = \min(K_{\psi_{old}}(p,\psi_{old}))\); so we obtain also:

\[
\sum_{i=1}^{(m+n)\psi_{old}} \frac{C_{\tau_i}}{T_{\tau_i}} < 1, \text{ in each processor } p \text{ for each reconfiguration scenario } \psi_{old} \text{ with } 1 \leq p \leq K, 1 \leq h \leq M. \text{ We can observe that our proposed approach provides an efficient or near-optimal global scheduling algorithm which schedules tasks according to EDF in each processor } p \text{ for each reconfiguration scenario } \psi_{old}. \text{ All tasks meet their deadlines after a reconfiguration scenario } \psi_{old} \text{ was applied at run-time. We can also observe, that our proposed algorithm selects tasks to migrate from one processor source } i \text{ to another processor destination } j \text{ in an optimal way such that overall utilization of task set is minimum. Parameters of tasks i.e., period, deadline and worst case execution time, are generated randomly. We have illustrated that our proposed algorithm outperforms other scheduling multiprocessor algorithms and a number of scheduling events are much lower than appearing in others.}

### 3 EXPERIMENTATION RESULTS

In this section, we analyze the performance of our proposed approach for both periodic synchronous and asynchronous tasks. The simulation runs on our tool RT-Reconfiguration and proven by the real-time simulator Cheddar (Singhoff L.M.F., 2004) with a task set composed of old tasks \(\xi_{\text{old}}\) and new tasks \(\xi_{\text{new}}\) in the processor \(p\) for each reconfiguration scenario \(\psi_{new}\). We illustrate this experimentation with a simplified example. The task set considered for this example is given in table 1 and it is composed now of 10 tasks. The sum of utilization of all tasks is given in table 1 and is equal to 426.1%. In table 1, the first column represents the task identifier, the second column represents the worst case execution time (WCET), the third column represents the period and the fourth column represents the deadline of each task which is less or equal to the period in this example of real time tasks.

<table>
<thead>
<tr>
<th>Task</th>
<th>(C_i)</th>
<th>(T_i)</th>
<th>(D_j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_1)</td>
<td>2</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>(\tau_2)</td>
<td>3</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>(\tau_3)</td>
<td>2</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>(\tau_4)</td>
<td>2</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>(\tau_5)</td>
<td>3</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>(\tau_6)</td>
<td>14</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>(\tau_7)</td>
<td>10</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>(\tau_8)</td>
<td>8</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>(\tau_9)</td>
<td>13</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>(\tau_{10})</td>
<td>5</td>
<td>11</td>
<td>12</td>
</tr>
</tbody>
</table>

We have 3 identical processors in our system to schedule these tasks. In this case, we assume that each task’s deadline is less or equal to its period. The worst case execution times, deadlines, and the time periods of all tasks are generated randomly.

In this experiment, our task set example is initially implemented by 5 characterized old tasks \(\xi_{\text{old}} = \{\tau_1; \tau_2; \tau_3; \tau_4; \tau_5\}\). These tasks are feasible
because the processor utilization factor $U = 1.19 \leq 3$. These tasks should meet all required deadlines defined in user requirements and we have $Feasibility(Current_{\text{old}}(t)) \equiv True$.

Firstly, tasks are partitioned: task $\tau_1$ is executed on first processor, $\tau_2$ and $\tau_3$ are executed on processor 2 while task $\tau_4$ and $\tau_5$ are executed on processor 3. We have three sets of local tasks.

We apply our contribution to this running example and we could observe that the recalibration points of the utilization factor, when parameters of new tasks are modified, decreases and becomes less or equal to 1 and we can deduce that the system is now feasible.

Indeed, if the number of tasks increases, then the overload of the system increases too.

Moreover, with this efficient solution, these tasks can be guaranteed to meet their deadlines after a reconfiguration scenario $\psi_h$ and were applied by an efficient EDF based scheduling algorithm on multiprocessor system. We assume that our proposed algorithm uses an independent task sets in order to minimize the interaction between tasks to limit the number of messages transmitted and overloads conditions. Finally, we verify also, the correctness of the whole system with minimizations of response times.

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