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Minimizing the cardinality of a real-time task set by automated task clustering

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ABSTRACT

The objective of this paper is first to properly define the notion of task clustering. This is the process of automatically mapping functionalities (blocks of code corresponding to a high-level feature) with real-time constraints to tasks (or threads). We aim at reducing the number of tasks functionalities are mapped to, while preserving the schedulability of the initial system. Second, our goal is to expose the complexity of the problem and to sketch methods we will propose for solving this problem. We consider independent tasks running on a single processor.

1. INTRODUCTION

Our work falls within the scope of real-time systems programming. Usually, real-time system developers design a system as a set of functionalities with real-time constraints. A functionality is here considered a block of code corresponding to a high-level feature. Implementing such systems requires to map each functionality to a real-time task (thread). On the one hand, the number of those functionalities is quite high. For instance, it ranges from 500 to 1000 in the flight control system of an aircraft or of a space vehicle [6, 10]. On the other hand, a large number of threads implies, a significant time overhead in context switching [23, 13] and an important memory footprint (e.g. task control block, size of the stack, etc.). Thus, the number of tasks supported by embedded real-time operating systems is limited, rarely over one hundred and developers cannot map each functionality to a different task. This mapping is currently mainly performed manually and, given the number of functionalities to process, this work can be tedious and error-prone.

In our work, we address this question from the scheduling point of view. We model a system as a set of tasks with real-time constraints, where each task is characterized by an execution time, an activation period and a deadline, in the same way as Liu and Layland's task model [16]. With respect to this model, functionalities can simply be considered as finer grain tasks, while threads are just coarser tasks. Thus, mapping functionalities to tasks amounts to gathering several tasks into a single one, which we call *task clustering*. Clustering several tasks implies to choose only one deadline for the cluster, which effectively reduces some task deadlines. As a consequence, we have to check that the system schedulability is preserved after the clustering. Our objective is to automate the clustering, so as to reach a minimal task number, while preserving the system schedulability.

Related Work.

In the literature, task clustering is most often studied in the context of distributed systems implementation, where it consists in distributing a set of tasks over a set of computing nodes (processors or cores). This is different from our context, because in the distributed

systems context a cluster corresponds to the set of tasks allocated to the same computing resource. For instance, [20, 1] aim at minimizing communications by clustering tasks that communicate a lot. The approaches in [19, 11] cluster tasks based on communications, in order to reduce the system makespan. The number of tasks of the resulting implementation is however not reduced.

Functionality to task mapping is known as runnable-to-task mapping and is identified as a step of the development process in the augmented real-time specification for AUTomotive Open System ARchitecture (AUTOSAR) [5]. This document and [23] also provide guidelines defining under which conditions runnables can be mapped to the same tasks. Authors in [26] propose an automated mapping in that context, but that work is restricted to functionalities that have deadlines equal to their periods. In [7, 18], the authors study the multi-task implementation of multi-periodic synchronous programs and must allocate the different elements of the program to tasks. The clustering is out of the scope of [18], while the heuristic proposed in [7] is very specific to the language structure.

In [22], authors aim at reducing the number of tasks in order to reduce the complexity of the scheduling problem. However, they only focus on functional requirements to group tasks, without considering timing constraints.

This research.

The number of possible clusterings of a task set is equal to the number of partitions of the set, which is close to the *Bell number* [21]. The Bell number is exponential with respect to the cardinality of the set. Thus, given the huge number of possibilities to explore, we motivate the use of a heuristic to tackle the task clustering problem. We also study the schedulability tests that can be applied to first, check the schedulability of a clustering and second, to constitute a relevant heuristic cost function. For now, we do not consider communications and the execution platform is made up of a single processor. These are strong restrictions, which will be lifted in future work. The aim of the present paper is to properly define the problem and to study it in a simple setting, so as to serve as a basis for future work.

Organization.

The rest of the paper is organized as follows. In Section 2, we describe our clustering model. Section 3 is dedicated to the complexity of the task clustering problem. We address the question of schedulability in Section 4. We describe the current status and the future work involved in Section 5.

2. PROBLEM DEFINITION

Our model, illustrated in Figure 1, is based on Liu and Layland's model [16]. A system consists of a synchronous (i.e. with offsets

equal to zero) set of real-time tasks $\mathcal{S} = (\{\tau_i(C_i, D_i, T_i)\}_{1 \leq i \leq n})$ where C_i is the worst-case execution time (WCET) of τ_i , T_i is the activation period, D_i is the relative deadline with $D_i \leq T_i$. We denote $\tau_{i,k}$ the $(k+1)^{th}$ ($k \geq 0$) instance, or *job*, of τ_i . The job $\tau_{i,k}$ is released at time $o_{i,k} = kT_i$. Every job $\tau_{i,k}$ must be completed before its absolute deadline $d_{i,k} = o_{i,k} + D_i$

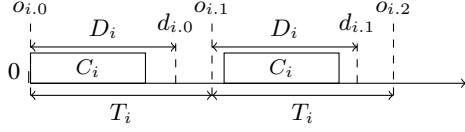


Figure 1: Task Diagram.

2.1 Scheduling

In this paper, we focus on priority-based scheduling policies, either fixed-job with Earliest Deadline First [16](EDF) or fixed-task priority policies with Deadline Monotonic [14](DM).

Let \mathcal{J} denote an infinite set of job, i.e., $\mathcal{J} = \{\tau_{i,k}, 1 \leq i \leq n, k \in \mathbb{N}\}$. Given a priority assignment Φ where 0 is the lowest priority, we define two functions $s_\Phi, e_\Phi : \mathcal{J} \rightarrow \mathbb{N}$, where $s_\Phi(\tau_{i,k})$ is the start time and $e_\Phi(\tau_{i,k})$ is the completion time of $\tau_{i,k}$ in the schedule produced by Φ .

DEFINITION 1. Let $\mathcal{S} = (\{\tau_i\}_{1 \leq i \leq n})$ be a task set and Φ be a priority assignment. \mathcal{S} is schedulable under Φ if and only if: $\forall \tau_{i,k}, e_\Phi(\tau_{i,k}) \leq d_{i,k} \wedge s_\Phi(\tau_{i,k}) \geq o_{i,k}$

In the sequel, we will also rely on the notion of *laxity*.

DEFINITION 2. Laxity L (or slack time) indicates the maximum delay that can be taken by the task without exceeding its deadline: $L_i = D_i - C_i$.

2.2 Clustering

Clustering τ_i and τ_j , where $D_i \leq D_j$, produces a cluster τ_{ij} with the following parameters:

$$C_{ij} = C_i + C_j$$

$$T_{ij} = T_i = T_j$$

$$D_{ij} = D_i$$

The cluster deadline is the shortest of the two tasks. Taking the minimum deadline ensures we respect both initial deadlines, even though the constraints will be, in general, more stringent than the initial constraints.

DEFINITION 3. Let $\mathcal{S} = (\{\tau_i\}_{1 \leq i \leq n})$ be a task set and τ_x and τ_y be two tasks of \mathcal{S} such that $D_x \leq D_y$. We say that τ_{xy} is a valid cluster if and only if:

1. $T_x = T_y$
2. $L_x \geq C_y$
3. The task set obtained after clustering is schedulable

In industrial practices, functionalities of different periods are sometimes mapped together, especially when these functionalities interact a lot, to minimize communication as explained in [24]. This possibility makes the clustering more complex because it requires to manage scheduling inside a cluster. For this reason, we do not

deal with this option in this paper. Nevertheless, we could relax this assumption via, e.g., hierarchical scheduling [15].

The laxity test is just an optimization. It is redundant with the schedulability test but it is simpler to check (constant time). Laxity is depicted in Subfigure 2(a).

A schedulable system might become non schedulable after clustering, as illustrated in Figure 2. Indeed, we notice in Subfigure 2(b) that the task τ_b misses its first deadline after the clustering of tasks τ_a and τ_c . Thus, we must check the resulting task set schedulability after clustering.

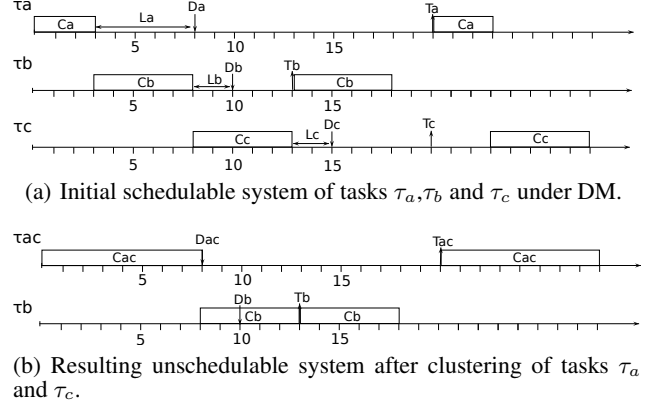


Figure 2: Influence of task clustering on system schedulability.

3. TASK CLUSTERING COMPLEXITY

We aim in this section at emphasizing the complexity of task clustering, which is related to the search space and to the schedulability test applied.

3.1 Search space

Our problem consists in finding a partition of the task set that is schedulable and with a minimum number of subsets. A partition of a set \mathcal{X} is a set of nonempty subsets of \mathcal{X} such that every element n in \mathcal{X} is in exactly one of these subsets. The number of partitions of a set is the Bell number [21]. The Bell number is exponential with respect to the size of \mathcal{X} and can be computed by the following recurrence relation:

$$B_{n+1} = \sum_{k=0}^n \binom{n}{k} B_k \text{ with } B_0 = 1$$

To give a better idea of the size of the search, notice that for instance, $B_{500} \simeq 10^{844}$.

To be more precise, as we only cluster tasks with identical periods, the search space can be restricted to $\prod_{i=0}^m B_{n_i}$ where B_{n_i} is the Bell number of the set of tasks with period T_i and m is the number of different periods of the whole task set. Nevertheless, this number remains exponential.

A naive approach might be to conduct an exhaustive search among all partitions of the initial task set, e.g. by applying partitions generation algorithms [2, 17], checking schedulability for each partition generated and choosing the partition with the least subsets. Nonetheless, our first experimentations show that, even using simple, non exact linear schedulability tests (presented below), this solution is not achievable due to the exponential number of partitions to explore. For instance, experiments conducted on a 2.3GHz Intel Core i7 quad-core with 4GByte memory, from an initial set of 20 tasks, lead to more than several days of computation. Thus, we propose to limit the exploration, by applying a heuristic.

dent is quite restrictive and will be lifted in future work. Situations where tasks of different periods may be gathered will also be studied.

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