# Stack Stealing

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***Abstract*—This paper presents an algorithm applied to schedule non-periodic jobs in hard real-time system, which is called "Slack stealing". A multitasking system process tasks according to priorties, and the slacks in periodic intervals are stolen and allocated to non-critical high-priority tasks. The system calculates and updates the dynamic amount of slack consumed and remained slacks. By utilizing idle time, the algorithm "Slack stealing" minimizes the average response time of non-periodic tasks, thereby improving overall scheduling performance.**

***Index Terms*—Slack, Hard real-time, aperiodic**

## I. Introduction

Today, real-time systems are applied to a variety of fileds. In a real-time system, a set of tasks must be executed and completed within a specific time duration. Failure to meet the deadline of the tasks oftentimes leads to catastrophic consequences. Periodic and aperiodic tasks coexist in hard real-time systems, and ideally, these aperiodic tasks should be handled without putting the critical tasks in jeopardy. For example, a system must perform a number of periodic operations to ensure its stable performance.On the other hand, some tasks are not carried out regularly but are triggered by aperiodic events, also require an response as early as possible.

## II. Introduction to Slack Stealing Algorithm

Slack Stealing Algorithm enables scheduler in a system schedule aperiodic tasks in slack time among periodic tasks and sporadic tasks. Scheduler keeps track of periodic tasks in order to calculate the amount of available slacks and consumed slacks, thus ensuring that time-critical tasks can be deferred without the risk of missing deadlines. These aperiodic tasks are handled by a slack stealer, which has the highest execution priority when there is any aperiodic task in the queue. If the queue is empty, the slack stealer is given the lowest priority and the execution is suspended. Slack stealing algorithm is called greedy since it constantly look for available slacks to schedule aperiodic tasks in the queue as soon as possible.

## III. Slack-Stealing in Clock-driven system

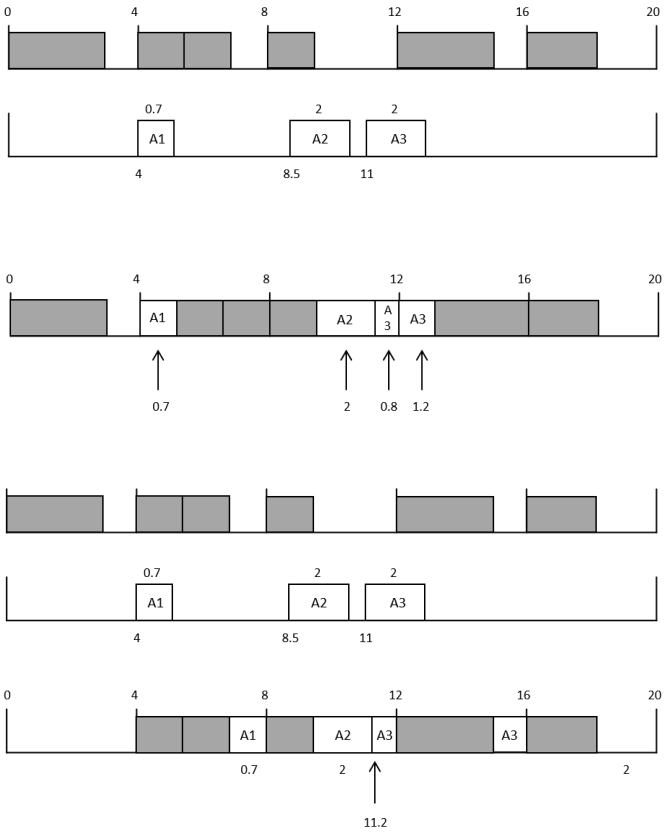
### A. Slack-Stealing in Clock-driven system

Safety-critical applications such as railroad systems, aircraft, or nuclear power plants are highly dependent on stable system performance, where every execution must be pre-processed and guaranteed to be absolutely correct. Due to the high degree of determinism, cyclic executives are therefore suitable candidates for such applications as described above. They are rather simple, reliable, and anomaly-free. Clock-driven scheduling is the foundation of cyclic executives, and it is applicable when the task parameters and resource requirements are known in advance. The system computes the schedule offline and stores them for use at run-time, and this scheduling decision is made periodically. By the initialization of each instance, the scheduler chooses and dispatches tasks. Clock-driven scheduling promises that all the periodic hard real-time jobs can be finished by their deadline. Nevertheless, the scheduler is also required to handle aperiodic tasks triggered by external events. Typically, hard real-time tasks have higher priority than aperiodic tasks, which means aperiodic tasks are scheduled in the background and processed after the completion of all hard real-time tasks. Typically, hard real-time tasks are prioritized over aperiodic tasks. Aperiodic tasks are scheduled in the background and delayed until all the tasks with a hard real-time deadline are completed. The delay of execution can lead to an undesirably long response time for aperiodic tasks, which becomes a design issue in the clock-driven system. Therefore an approach is proposed to resolve this problem. The approach is called Slack-stealing, and its objective is to minimize the response time of periodic tasks. In real-time systems, completing a hard real-time task early is pointless, as long as it finishes by its deadline. Note that the sooner the aperiodic tasks are processed, the sooner the system responds. Since the early completion really brings no benefit but reduces efficiency, the strategy is to safely delay those tasks without missing the deadline and give higher execution priority to aperiodic tasks whenever possible.

### B. Basic slack computation

Assuming that the amount of time allocated to slice in the frame Fk is denoted by Xk, the slack during frame Fk can be expressed as Sk in the following formula: Sk = Fk - Xk. Whenever Sk is large than 0, in other words, the aperiodic tasks queue is nonempty, the cyclic executive gives Slack stealer the highest execution priority to process aperiodic tasks. As long as Sk is non-zero, tasks will never miss any deadline. Cyclic executives must keep track of the number of available slack and the consumed slack, and this can be done by an interval timer. At the beginning of each cycle, the

interval timer is set to the value of the initial slack in the frame. The timer counts down as Slack stealer consumes the available slack. When the value comes to 0, the timer expires and the cyclic executive suspends Slack stealer, returning the highest execution priority to periodic tasks. Note that some senior operating systems do not support high-resolution timers, so this method is only applicable if the system can guarantee granularity and accuracy in hundreds of milliseconds or seconds. After periodic tasks finish by their deadline, before the next instance, the scheduler again examines the aperiodic task queue and repeats the same procedure. Figure 1 provides an illustrative example of background scheduling in clock-driven system. The gray-shaded blocks in the top queue stand for hard real-time tasks which are executed periodically. Cyclic executives initiate a new cycle every 4 time units. Beneath the top queue lies the aperiodic tasks queue. The first aperiodic task arrives at the time 4 and has 0.7 units of execution time. The second and the third aperiodic tasks come at the time 8.5 and 11 respectively, and both execute for 2 time units. As shown in the figure, the scheduler dispatches periodic tasks first and starts executing aperiodic tasks afterward. The first aperiodic task A1 arrives at time 4 and completes execution at time 8, which requires a response time of 4 units. The response time for A2 is 2.7 time units. Task A3 starts executing 0.8 time units after A2, and it is preempted due to the deadline. In the next frame, A3 resumes execution and finishes at time 16, with a response time of 4.8.




| | A1 | A2 | A3 |
|---|---|---|---|
| Background Scheduling | 4 | 2.7 | 4.8 |
| Slack Stealing | 0.7 | 2.7 | 1.7 |

In Figure 2, the scheduler adopts the slack stealing approach to process the same task queues. Instead of prioritizing the hard real-time tasks first, the scheduler defers them and executes aperiodic tasks first to achieve a shorter response time. At time 4, a new execution cycle begins with the arrival of task A1. The aperiodic task queue is non-empty so the scheduler dispatches A1 first. After 0.7 time units, the available slack time is completely consumed, so the scheduler suspends the stack stealer and continues with the remained periodic tasks in the frame. At time 8 starts the new frame, the periodic task executes directly since the aperiodic task queue is empty at this time. At time 10, A2 takes over the priority of execution and proceeds with A3 after its completion. Finally, A3 pauses at time 12 and resumes execution, finishing at 13.7.

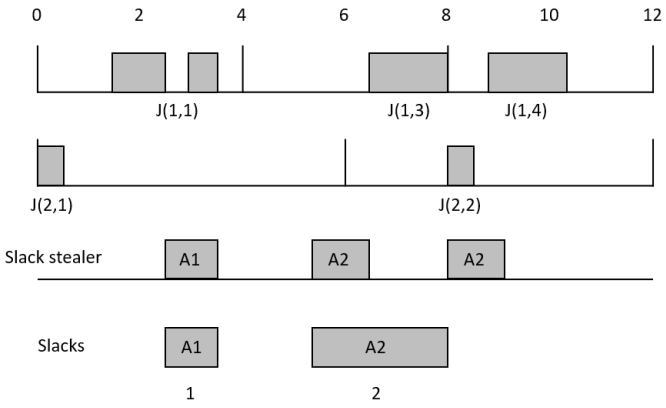
### *C. Background Scheduling and Slack stealing*

A comparison is made to show the difference in response time of background scheduling and slack stealing. By and large, aperiodic tasks have a relatively short response time when slack stealing is adopted.(see figure.3) As described in the previous section, clock-driven systems are widely deployed in safety-critical applications due to their high level of reliability and predictability. However, these characteristics also imply that clock-driven systems are rather inflexible. Any changes in temporal parameters, even minor ones, require a complete rescheduling. The constant modifications of systems would increase the cost of development and time to market, which are undesirable. Therefore, for systems with diverse timing parameters and resource requirements, an alternative scheduling approach must be introduced. Priority-driven systems refer to the system that schedules tasks based on their deadline or other timing constraints. Rather than doing pre-calculation, the priority-driven approach makes scheduling decisions when pre-emption is allowed, i.e when the release or completion of a task occurs. In principle, priority-driven algorithms always make locally optimal scheduling decisions, trying to exploit any possible resource, which is described as greedy. Moreover, priority-driven algorithms never intentionally leave resources idle, as they would contradict the concept of locally optimal decisions. The term starvation refers to a phenomenon regarding low-priority tasks waiting indefinitely in a priority-driven schedule. In some cases, the scheduler lets tasks with lower priority wait indefinitely. For instance, in a system that is heavily loaded with high-priority tasks, the completion time of low-priority tasks can be difficult to estimate.

## IV. Slack stealing in Priority-driven system

In principle, slack stealing in a priority-driven system works in a similar way to how it works in a clock-driven system. The core function is to compute and keep track of the amount of slack in the systems. However, slack stealing is

computationally more complex in a priority-driven system. Figure 3 gives an example of how slack stealing contributes to improving the response time of aperiodic tasks in a priority-driven system, where the scheduling of periodic tasks is on the the basis of earliest-deadline-first (EDF) algorithm.



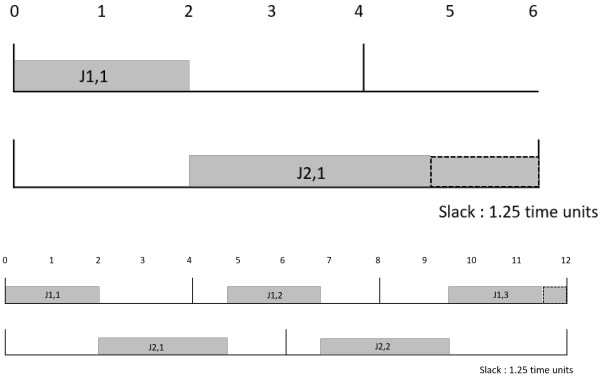

Consider that an EDF system consists of two periodic tasks T1(4,1.5) and T2(6,0.5). Aperiodic tasks A1 and A2 are released at time 2.5 and time 5.5 respectively. At the start, the aperiodic task queue is empty so the Job J(2,1) executes first. The slack stealer resumes execution as the first aperiodic task arrives at time 2.5, which has an execution time of 1 time unit. After A1 is finished, J(1,1) proceeds with the rest of the execution which is postponed to time 3.5. The second aperiodic task A2 is released shortly after, and the slack stealer continues because the periodic task queue is empty by then. The available slack is completely consumed at time 6.5 and the slack stealer is suspended. The scheduler carries on executing periodic task J(1,2) and finishes at time 8. At the beginning of the next frame, the slack stealer is again freed from suspension and then completes the rest part of A2.

## V. Slack computation

Slack computation algorithms refer to the algorithms that calculate and update the amount of available slack in the system. A slack computation algorithm is considered correct when it correctly reports the presence of a slack. An incorrect computation may result in a missed deadline, which is not acceptable in any real-time system. Slack computation can be either static or dynamic. In the case of a clock-driven system, the slack is calculated using a static computing approach. The scheduler calculates all the slack based on given temporal parameters and other information regarding periodic tasks before run-time. This is called offline computation. During run-time, the scheduler only needs to update the current information. Therefore, the static approach has a relatively low run-time overhead. However, the problem with this approach is that it has a rather low jitters tolerance. When the actual release time of a periodic task differs from the release time used to generate the message, the pre-computed slack may be incorrect, leading to serious consequences. A dynamic approach calculates the amount of slack during the run-time and it is applied when the periodic tasks have a wide range of inter-release time. High run-time overhead is an apparent drawback of dynamic slack computation. However, the dynamic approach can be integrated with unused processor run-time and task overruns.

### A. Static-slack computation

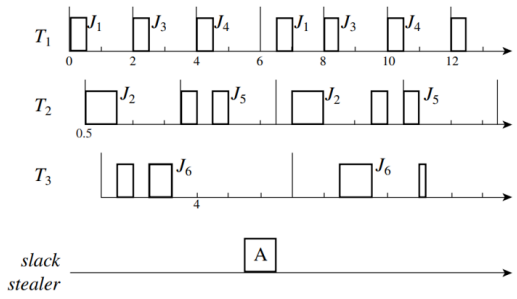
As the number of tasks increases, the complexity of the slack calculation can be quite high. Figures 4 and 5 give an illustrative example of how the relaxation calculation is performed and the problems that exist. In Figure 4, a system is performing two periodic tasks T1 (4,2) and T2 (6,2.75). Since the total execution time required to complete these two tasks by the deadline of J2,1 is 1.25 (allocated time - execution time of T1 - execution time of T2), it is intuitive to assume that this system has a slack of 1.25 time units.




However, this assumption is only correct within this time slot. As the time scale expands, it may lead to a false slack computation, causing the deadlines to be missed. For example, in Figure 5, where the system takes J1,3 and J2,2 into account, there may be a situation where J1,3 misses the deadline because the system assumes that the available slack time is 1.25 time units, when in fact it is only 0.5 time units.

An optimal static-slack computation algorithm is proposed as a convenient way to analyze the complexity of the calculation of slack in the system. The algorithm contains n periodic tasks in an N square size table and assumes that the system actually releases the periodic tasks periodically. (see Figure 6) For a better understanding of the algorithm, the boundaries of the tasks can be ignored, i.e., it does not matter to which task each job belongs. It creates a hyper period that contains jobs labeled with a corresponding serial number, e.g. J1, J2, J3,...Jk. The algorithm represents the deadline of each job as dn (n = nth job) and indexes all jobs in non-increasing priority order. Consider tc to be the time at which the slack calculation occurs and i(tc) to be the amount of slack in a periodic job at time tc. The amount of slack i(tc) is the result of the total allocated time minus the total time required for the selected job to complete its execution. The slack of individual jobs changes over time once the system starts execution. However, the processor idles, execution of lower priority jobs, and the execution of the slack stealer are not taken into account in the precomputed initial slacks. Therefore, if any of the above

events occurs, it takes up a portion of the slack, making the total amount of pre-computed slack smaller.




| $W(i,j)$ $i$ \ $j$ | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| 2 | | 2 | 2 | 2 | 2 | 2 |
| 3 | | | 2 | 2 | 2 | 2 |
| 4 | | | | 3.5 | 3 | 2.3 |
| 5 | | | | | 3 | 2.3 |
| 6 | | | | | | 2.3 |

In Fig. 6, the execution of job j6 lasts 0.5 time units before time 2, but these 0.5 time units are not taken into account by the pre-computed initial slack of J3. At time 2, the slack of J3 has a value of 1.5 instead of 2 units of time. In addition, since the slacker performs 0.5 time units of work at the beginning of the second time period, it reduces the total slack by 2 time units for all jobs in this time period.

### *B. practical consideration*

In general, there are two important factors to consider when analyzing the implementation of static slack computation: the effect of phase and the effect of release time jitter. Through observing the precomputed static-slack graph it can be seen that the end of the first hyper period may differ from the end of a busy interval of the periodic tasks in the absence of aperiodic jobs. Therefore, when the periodic tasks in the system are out of phase, ignoring this difference will lead to an incorrect calculation of the initial amount of slack, which will result in missed deadlines. As it exemplifies in figure 7 when the hyper period and the busy interval both end at the same time, the schedule executes cyclicly with a fixed period without aperiodic tasks and release-time jitters. If the mentioned conditions are satisfied, it is sufficient to compute the slack in the first hyper period and apply them to all times in the system. On the flip side, when the hyper period comes to the end early than the busy interval, there exists an initial transient segment that ends at the end of the first busy interval and is proceeded with a fixed cyclic period. Release-time jitters are another common issue existing in periodic task models and priority-driven algorithms. In most cases, when the jitters are of negligibly small size, the priority of jobs remains correct and does not require any change. Considering that the jitter of the release time is relatively larger than the interval between the deadlines, the pre-calculated values will no longer be correct and the jobs in the system will need to be rescheduled. Again figure 7 provides insights into this issue. Assume that periodic job J3 is postponed till time 2.1 whereas the job J4 is delayed to time 4.3. Except for J3 and J4, the rest of the jobs in the hyper period are released as scheduled. According to the precomputed slack table, the initial slack for the jobs J1, J3, and J4 are 1.5, 2, and 3.5 respectively.While the deadline of job J1 is still time 2, the deadline of J3 and J4 are 4.1 and 6.3. Assuming that J5 has a small delay (0.1 units of time), the actual slack of J5 would have an additional slack of 0.1 compared to the result of the pre-conputed slack table. In this case, despite the release time is delayed, the results given by the pre-computed slack table are still applicable to the rest of the jobs. In this case, the results given by the pre-computed slack table are still applicable to the rest of the jobs, despite the delay in release of J5. This creates a lower bound of the actual initial slack in the system.

### *C. Dynamic-slack computation*

To confront the unavoidable release-time jitters, the system would make use of dynamic computation inn run time. It is achieved by computing lower bounds on the relaxation without relying on a priori information.

## REFERENCES