A loadable task execution recorder for Linux

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***Abstract*—This paper presents a task recorder for Linux-based operating systems, in the form of a loadable kernel module. To the best of our knowledge, this is the first Linux task recorder which does not require kernel patches (kernel modifications). This complies with the requirements in the area of embedded systems where reliability and stability are important properties, hence, proven versions of Linux are therefore preferred.**

The implementation is based on the loadable real-time scheduler framework RESCH (REal-time SCHeduler). RESCH uses only exported Linux kernel primitives as a means for controlling scheduling. The disadvantage with this solution is that it can only detect scheduling events of the tasks being scheduled by RESCH itself, since it can not directly manipulate nor have knowledge of the tasks in the Linux task ready queue. In order to verify the correctness of the task recording, a comparison has been made with a second recorder, which uses a kernel patch. Our tests indicate that the new, RESCH-based, recorder gives identical results[1].

I. Introduction

The overall aim of our research is the development of hierarchical scheduling. Hierarchical scheduling has several advantages, stretching from enabling design time parallel development of system parts, simplifying integration, to runtime temporal partitioning and safe execution of tasks. Our previous work includes practical issues of this kind of scheduling [1] as well as the theoretical advantage [2] of this scheduling technique, in real-time systems. However, the hierarchical scheduling technique is rarely an integrated part of an operating system (except for, e.g., ARINC653 compliant operating systems that are commonly found in avionics applications). Indeed, there is a need to develop/implement new scheduling algorithms, such as hierarchical scheduling, in the area of real-time systems. Looking from a practical point of view, it is an advantage if hierarchical scheduling (and other scheduling techniques) can be implemented easily and efficiently without modifying the kernel. The latter makes it easier for both developers and users since there is no need to maintain/apply kernel patches (kernel modifications) every time the kernel is replaced/updated. Moreover, keeping the scheduler isolated in a kernel module, without modifying the kernel, simplifies debugging and potential certification of its correctness (component-based development advantages). We see that RESCH [3] is useful because it has the advantages mentioned.

RESCH is a scheduling framework intended to make life easier for scheduler developers in Linux based RT/GP OSs (Real-Time/General Purpose Operating System). A key motivation for using RESCH is that it does not need any kernel modifications, secondly, it makes scheduler development easier because it abstracts the complexity of scheduling aspects and presents a simple and easy scheduling interface to the user. However, while development of schedulers are simplified with this framework, it lacks support for debugging the schedulers. Our vision is to make the RESCH framework a complete scheduler development base. We want it to have all necessary tools for creating schedulers, and everything should be totally independent of kernel patches. This also has the advantage that it is easy to develop RESCH for other platforms, hence, making scheduler development platform independent. In order to comply with our vision, we want the integrated debugger in RESCH to be free of kernel patches as well.

With this paper, we present a task execution recorder, which is capable of debugging schedulers. The task recorder (we will refer to it as a recorder for the rest of the paper), is able to record the following scheduling events during run-time:

1) The time instance when a task is released (even though it might not start to execute).
2) The time instance when a task starts to execute.
3) When there is a task switch, the recorder distinguishes between preemption and non-preemption.
4) The time instance when a task finishes its execution.

The output from the recorder is a simple text-file containing task switch events. We have converted this file format to fit the trace visualization tool Tracealyzer[2].

A. System model

We assume fixed priority preemptive scheduling of periodic tasks, according to the periodic task model [4]. A task i is presumed to have the following parameters, $\langle T_i, WCET_i, D_i, pr_i \rangle$, where the period T_i represents the frequency in which the task is released for execution, $WCET_i$ is the worst case execution time of the task, the relative deadline D_i (within the period) is when the task must complete its execution (RESCH monitors this) and pr_i is the task priority (higher value represents higher priority). Also, all tasks are assumed to execute on the same core, i.e., single-core.

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[2]For more information about Tracealyzer, see http://www.tracealyzer.se/

B. RESCH

As mentioned previously, RESCH is a patch-free scheduling framework for Linux. It supports periodic tasks which can be scheduled in a fixed-priority preemptive manner. RESCH runs as a kernel module (in kernel space), giving both an interface to users in user space (e.g. a task specific interface like `rt_wait_for_period()`) as well as in kernel space. The kernel space API (Application Programming Interface) has the interface shown below:

1) **task_run_plugin( )**
2) **task_exit_plugin( )**
3) **job_release_plugin( )**
4) **job_complete_plugin( )**

These functions can be implemented by a **RESCH plugin** (Figure 1), i.e., a kernel module that has access to the RESCH kernel API. These functions are called in **RESCH core** at certain events. Functions 1) and 2) are executed every time a task registers/unregisters to RESCH. With register we mean that the task does a RESCH API call, transforming it to a **RESCH task**, which creates a RESCH TCB (Task Control Block) and puts it in the RESCH ready-queue etc. A RESCH TCB has, among other real-time specific data, a reference to its corresponding Linux task TCB (**task_struct**). The primitives 3) and 4) are called whenever a RESCH task is released for execution or when it has finished its execution. The plugins get these scheduling notifications and can thereby affect scheduling, trace tasks etc.

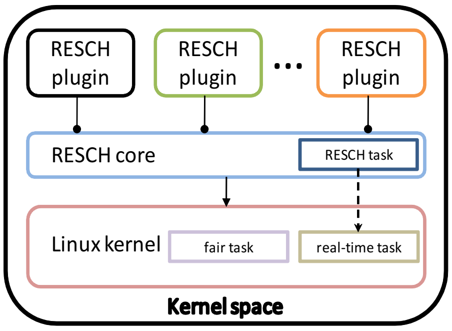


Fig. 1. RESCH framework

In Linux, since kernel version 2.6.23 (October of 2007), tasks can be either a **fair task** or a **real-time task**. The latter group has higher priority (0-99 where 0 is highest) than fair tasks (100-140). A task that registers to RESCH is automatically transformed to a real-time task. RESCH is responsible for releasing tasks, and tasks registered to RESCH must notify when they have finished their execution in the current period. In this way, RESCH can control the scheduling. RESCH uses an absolute-time clock, i.e., it does not wrap around. Also, release times are stored as absolute values, so release patterns are exact.
The cost of having a patch-free solution is that RESCH can only see scheduling events related to its registered tasks, i.e., higher priority real-time tasks, which are not registered in RESCH, can thereby interfere with RESCH tasks without the RESCH core detecting it. A simple solution to this problem is to schedule all real-time tasks with RESCH.

C. Task-switch hook patch

Our previous work [5] includes an implementation of a **task_switch_hook** (Figure 3), residing in a kernel module, which is called by the Linux scheduler at every scheduler tick. This solution requires modification of two code-lines in two separate kernel source files (*sched_rt.c* and *sched_fair.c*). The modification of file *sched_rt.c* is illustrated in Figure 3 (a similar change is done in *sched_fair.c*). Linux has (since kernel version 2.6.23) two scheduling classes, namely the *fair* and the *real-time* scheduling classes. When a new task should be released, the Linux scheduler iterates through its scheduling classes (first the *real-time* class, secondly the *fair* class) in order to find the next task to release. This is shown in Figure 2.

```
class = sched_class_highest;
for (; ; ) {
      p = class->pick_next_task(rq);
      if (p)
            return p;
      class = class->next;
}
```

Fig. 2. Kernel function: **pick_next_task**

The modification (Figure 3) makes it possible to re-direct a scheduling class' function **pick_next_task** to a user defined function (i.e., our function **task_switch_hook**), in a kernel module. This function (hook) can be inserted and removed during runtime.

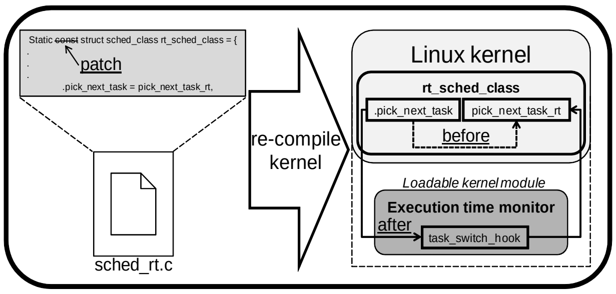


Fig. 3. Hook patch

In this paper our overall goal is to implement a patch-free task execution recorder in Linux for debugging purposes, i.e., which can be useful for a scheduler or application developer. Our solution enables debugging on any Linux-based RT/GP OS, as long as the Linux interface is not changed, since RESCH and the recorder are both loadable kernel modules that calls the Linux kernel functions. Hence, our recorder is more general than patched solutions since it is difficult to port these between different platforms.

The main contributions of this paper are:

1) We have implemented a (patch-free) task recorder with the use of RESCH, which enables debugging at task level, in Linux based RT/GP OS.

2) We have evaluated our solution by implementing yet another (patched) recorder, using the technique presented in [5], and compared the results from the two recorders.

The outline of this paper is as follows: in Section II we describe the two recorder implementations. Section III compares the trace result from the two recorders. Section IV presents related work, and finally, Section V concludes.

II. Implementation

The following section presents a recorder implementation based on RESCH, and a second implementation based on a hook patch [5].

A. RESCH plugin recorder

The recorder is implemented as a plugin (see Figure 1) in RESCH. Although, it could also become an integrated part of RESCH core at a later stage.

It is important to note that in order for the recording to be correct with this plugin, no higher priority real-time tasks (that are not registered by RESCH) are allowed to run. Also, the current recorder implementation does not support multi-core, hence, *load balancing* must be disabled (a function in Linux that migrates tasks to other CPUs based on load). Support for multi-core is possible, but without *load balancing*. The reason is that RESCH cannot detect task migrations made by the Linux scheduler.

Figure 4 shows the necessary data needed to store a scheduling event (i.e. task switch). The member **rid** is the index to the RESCH task TCB. We use this identifier because is has a smaller range than the Linux task id (PID), and thereby require less memory. The **timestamp** is stored in micro-seconds, i.e., our recorder can record approximately 35 minutes (assuming we have 32 bits) since we use one bit for storing the preemption flag (informing whether there has been a preemption or not).

```
struct task_switch_event {
  char next_rid; // rid (0 − 64) is the RESCH task id.
  char prev_rid;
  unsigned int timestamp; // Bit nr 31 hold preempt. flag.
};
```

Fig. 4. Event structure

`task_run_plugin`, line (1) Figure 5, is called every time a task registers to RESCH. Since the current version of our recorder does not support multi-core, we migrate all tasks to one CPU (CPU #0 in this case).

Figure 5 show parts of the recorder implementation (in simplified form) in RESCH. Line (4) and (18) (Figure 5) are called by the RESCH core at every task release and completion. In this way, not only can we record task switches, but also detect when a task is released and also show this information graphically in the Tracealyzer.

```
1: void task_run_plugin(resch_task_t *rt) {
2:    migrate_task(rt, 0); // Migrate all tasks to CPU 0.
3: }
4: void job_release_plugin(resch_task_t *rt) {
5:    resch_task_t *curr;
6:    int timestamp;
7:    timestamp = linux_timestamp_microsec( );
8:    curr = active_highest_prio_task(rt->cpu_id);
9:    if(curr == NULL) {
10:      store_event(IDLE, rt, NO_PREEMPT, timestamp);
11:      return;
12:   }
13:   if(rt->prio > curr->prio)
14:      store_event(curr, rt, PREEMPT, timestamp);
15:   else
16:      store_event(curr, rt, NO_PREEMPT, timestamp);
17: }
18: void job_complete_plugin(resch_task_t *rt) {
19:   resch_task_t *next;
20:   int timestamp;
21:   timestamp = linux_timestamp_microsec( );
22:   next = active_highest_prio_task(rt->cpu_id);
23:   if(next == NULL)
24:      store_event(rt, IDLE, NO_PREEMPT, timestamp);
25:   else
26:      store_event(rt, next, NO_PREEMPT, timestamp);
27: }
28: void store_event(resch_task_t *prev, resch_task_t *next,
29:                      char preempt, unsigned int timestamp) {
```

Fig. 5. Recorder implementation

B. Hook patch recorder

As mentioned previously, our patched recorder is based on a task-switch hook implementation [5]. This implementation consists of two hooks. One hook is executed when Linux calls the scheduling class *real-time*, the other one when *fair* class is called. The two hooks are never called in the same scheduler tick, only one of them (depending on if there are any real-time tasks eligible to execute). We use the similar data-structures in this implementation as the one presented in section II-A. A difference between the two approaches is that the hook patch implementation only detects a switch between tasks, i.e., it cannot know when a task is released (for which the RESCH implementation can). This will differentiate the trace results a bit.

III. Evaluation

We have tested our RESCH plugin recorder by running it in parallel with the hook patch implementation, i.e., the two recorders recorded the same trace at the same time. The recorder we compare with [5] was chosen because of its simplicity (easy to install, load/unload, modify source code etc.), small amount of source code and the fact that it records correctly since its hook is placed at the point where the Linux scheduler does the task context switches. We ran the task set in Table I on an Intel Pentium Dual-Core (E5300 2,6GHz) platform, equipped with a Linux kernel version 2.6.31.9, running with *load balancing* disabled. The recorded tasks ran on the same core, i.e., all tasks were migrated to CPU #0 at initialization phase. The trace from both implementations are visualized in Figure 9 and 10 with the Tracealyzer application. The tasks were scheduled by the RESCH core scheduler (i.e., we used no plugin scheduler) according to the parameters in Table I.

Name	T	$WCET$	D	pr
rt_task1	4	1	4	4
rt_task2	5	1	5	3
rt_task3	8	2	8	2
rt_task4	9	2	9	1

TABLE I
TASK SET USED IN THE EXPERIMENTS

Note that the absolute time-line in Figure 9 is 1 second behind Figure 10, but the relative time should match eachother since they were executed at the same time. The task ID:s in Figure 6 are the new modified PIDs (which are needed in order to reference RESCH TCBs from native Linux TCBs) and therefore different than the ones in Figure 7, which are the native PIDs.

If the user marks a task fragment, Tracealyzer will display a red box (e.g. task **rt_task4** in Figure 9 and 10) around the task instance, if it can detect the instance (which is not the case in Figure 10). In Figure 9 though, the Tracealyzer can separate between task instances, since the plugin recorder records task releases, e.g. line 20-21 in Figure 7, which represents the fourth fragment of **rt_task4** in Figure 9.

Figure 6 and 7 shows the data recorded by both recorders. The data is represented in the format: prev: <id1> <name1> next: <id2> <name2> <t-stamp> <preempt>, where **id1** and **name1** represents the task id and name of the task that is finishing (possibly preempted), **id2** and **name2** represents the task id and name of the task that is starting to execute, **t-stamp** is the timestamp in absolute time when this event has occurred and the flag **preempt** is set to 1 or 0 depending on if there is a preemption (1=preemption). The recorded data (Figure 6 and 7) corresponds to the graphical representation (Figure 9 and 10) from the start of the graphs (4.350.156 respectively 3.350.160) to the marked time-lines (14.354.148 respectively 13.354.149). The time in the graphs are represented in the format **second.milli-second.micro-second**. The difference in time (1 second) is due to that both recorders record absolute timestamps (and the tool visualizes in absolute time) and one recorder was started approximately 1 second before the other one.

```
1:  prev: 0 idle next: 32769 rt_task1 3350160 1
2:  prev: 32769 rt_task1 next: 32770 rt_task2 4266631 0
3:  prev: 32770 rt_task2 next: 32771 rt_task3 5183029 0
4:  prev: 32771 rt_task3 next: 32772 rt_task4 7038580 0
5:  prev: 32772 rt_task4 next: 32769 rt_task1 7350149 1
6:  prev: 32769 rt_task1 next: 32772 rt_task4 8266565 0
7:  prev: 32772 rt_task4 next: 32770 rt_task2 8354148 1
8:  prev: 32770 rt_task2 next: 32772 rt_task4 9270908 0
9:  prev: 32772 rt_task4 next: 0 idle 10726636 0
10: prev: 0 idle next: 32769 rt_task1 11350157 1
11: prev: 32769 rt_task1 next: 32771 rt_task3 12266246 0
12: prev: 32771 rt_task3 next: 32770 rt_task2 13354149 1
```

Fig. 6. Recorded data (Hook patch)

```
1:  prev: 0 idle next: 3900 rt_task1 4350156 1
2:  prev: 3900 rt_task1 next: 3901 rt_task2 4354149 1
3:  prev: 3901 rt_task2 next: 3900 rt_task1 4354159 0
4:  prev: 3900 rt_task1 next: 3902 rt_task3 4354150 1
5:  prev: 3902 rt_task3 next: 3900 rt_task1 4354160 0
6:  prev: 3900 rt_task1 next: 3903 rt_task4 4354151 1
7:  prev: 3903 rt_task4 next: 3900 rt_task1 4354161 0
8:  prev: 3900 rt_task1 next: 3901 rt_task2 5266627 0
9:  prev: 3901 rt_task2 next: 3902 rt_task3 6183025 0
10: prev: 3902 rt_task3 next: 3903 rt_task4 8038576 0
11: prev: 3903 rt_task4 next: 3900 rt_task1 8350148 1
12: prev: 3900 rt_task1 next: 3903 rt_task4 9266561 0
13: prev: 3903 rt_task4 next: 3901 rt_task2 9354147 1
14: prev: 3901 rt_task2 next: 3903 rt_task4 10270905 0
15: prev: 3903 rt_task4 next: 0 idle 11726633 0
16: prev: 0 idle next: 3900 rt_task1 12350153 1
17: prev: 3900 rt_task1 next: 3902 rt_task3 12354149 1
18: prev: 3902 rt_task3 next: 3900 rt_task1 12354159 0
19: prev: 3900 rt_task1 next: 3902 rt_task3 13266243 0
20: prev: 3902 rt_task3 next: 3903 rt_task4 13354147 1
21: prev: 3903 rt_task4 next: 3902 rt_task3 13354157 0
22: prev: 3902 rt_task3 next: 3901 rt_task2 14354148 1
```

Fig. 7. Recorded data (RESCH plugin)

The difference between the two traces is that the RESCH plugin recorder records task releases by recording a fake preemption and running the released task for 10 micro-seconds, e.g., lines 1-7 in Figure 7, though this is not the case (its just for visualization). Although, this enables the Tracealyzer to calculate and show the response time of a task. Other than that the preemption depth differs in the two traces (due to that the two recorders record preemption differently), the traces are almost identical (the recorded time points may differ a few micro-seconds at most). Figure 8 shows the RESCH plugin trace, visualized with the tool Grasp [6]. The tasks vertical positions are ordered by priority with the lowest priority at the top (including the idle task) and the time is scaled down 100000 times. The figure clearly shows the task frequency.

IV. RELATED WORK

The idea of our solution is based on the replay debugging approach [7], which records system events online and replays them offline. In later work [8], the replay debugging has been extended to be compiler- and OS-independent. While the replay debugging works with off-the-shelf compilers for application-level debugging, our solution is self-contained software using Tracealyzer [9] for OS-level debugging, and it is primarily focused on real-time scheduler debugging.

The SCHED_DEADLINE project [10], which is in charge of the EDF scheduler implementation for Linux, has used the sched_switch tracer provided by the Ftrace toolkit [11] to output the records of context switches. The output logs are then converted to the VCD (Value Change Dump) format so that GtkWave can visualize the task execution traces. The trace can of course be converted to the Tracealyzer or Grasp [6] format. Given that Ftrace is supported by the Linux community, it is reasonable to use this toolkit to trace task executions for kernel debugging, but it is dedicated to the Linux kernel, so it is not necessarily suitable for real-time scheduler debugging. For instance, sched_switch does not catch job releases, however,

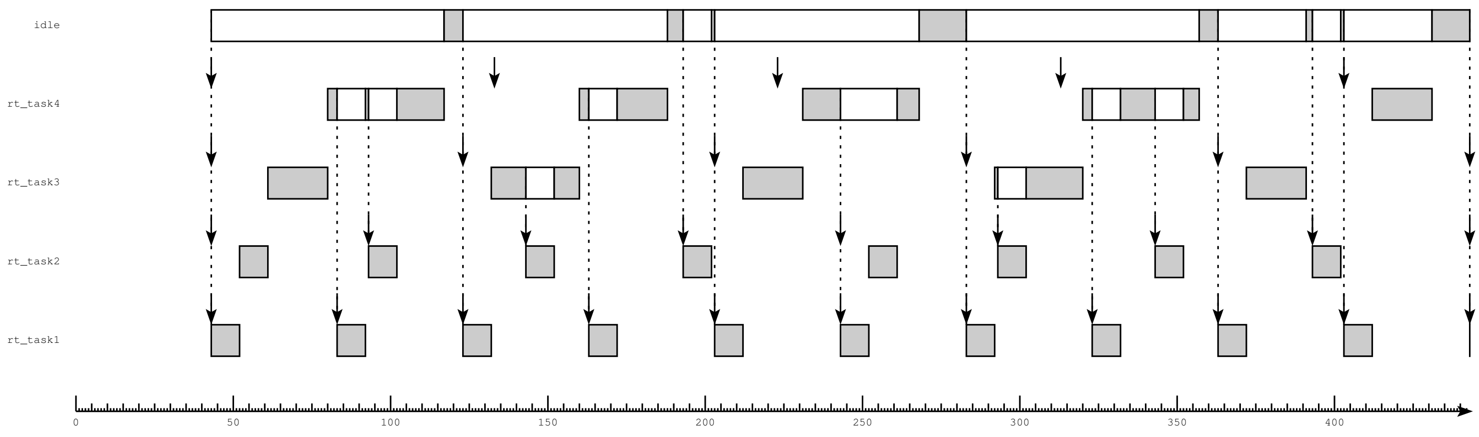
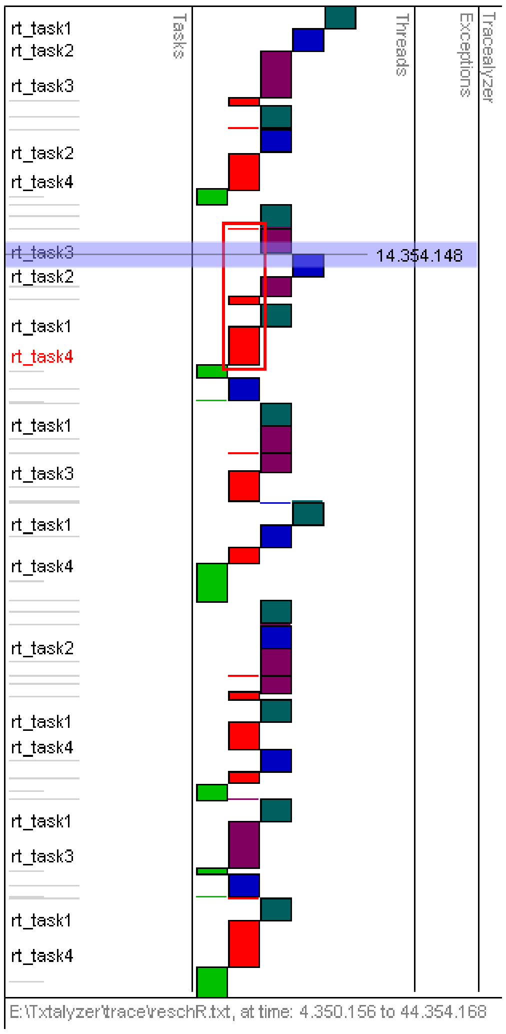
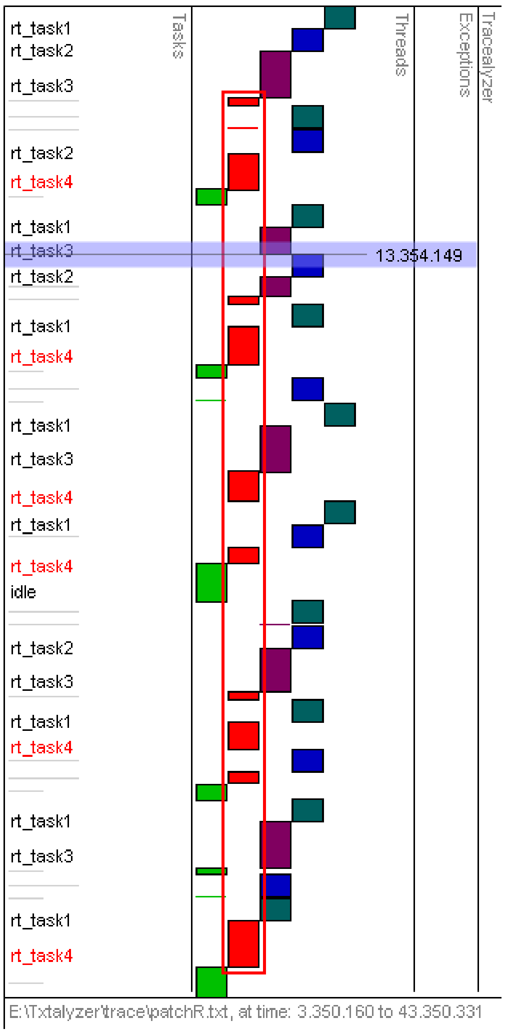


Fig. 8. RESCH plugin trace visualized with Grasp [6]



E:\Txtalyzer\trace\reschR.txt, at time: 4.350.156 to 44.354.168

Fig. 9. Example trace with RESCH plugin



E:\Txtalyzer\trace\patchR.txt, at time: 3.350.160 to 43.350.331

Fig. 10. Example trace with hook patch

context switches are precisely traced and it can distinguish between task completions and task preemptions. Our solution is more flexible and integrated in that it is available not only for the Linux kernel but also for other OSs, once the RESCH framework is ported.

DTrace [12], SystemTrap [13], LTT [14], and LTTng [15] are advanced tools for OS debugging. They are oriented for tracing entire kernel events, so it is required that the developers, in a high degree, understand how to use them. Meanwhile, our solution is more simplified by focusing on real-time scheduler debugging, and it is very easy to use in practice.

Real-Time Application Interface for Linux (RTAI) [16] is a collection of loadable kernel modules and a kernel patch which together provides a rich real-time API to the user. It gives the possibility to add/delete hooks for every task-start, task-switch and task-delete. These hooks give the possibility to monitor task execution in a detailed level.

V. Conclusion

We have implemented a task execution recorder in a stock Linux kernel, without applying kernel patches, with the use of the loadable real-time scheduler framework RESCH. The recorder is able to record task releases (with or without preemption) and task switches. The recorded data is later converted, offline, to a format suitable for the visualization tool Tracealyzer. In this way, the trace can be visualized graphically. The assumptions made, in order for the tracing to be correct, are that there should not exist any (unregistered RESCH) tasks that have higher priority than the (RESCH) tasks to be recorded, and that *load balancing* is disabled. Our results indicate that our recorder does a correct trace, by comparing the results with a trace made by a patched recorder. The second (patched) recorder is assumed to trace correct, since it is called by the Linux scheduler at every scheduler tick. The two recorders were executed in parallel, i.e., they recorded the same trace. Hence, an exact comparison is possible since the execution time of the tasks will be the same in both cases, and will therefore not affect the comparsion results. We showed that our recorder got the same trace result as the patched solution (with only a few micro-seconds of difference).

As future work we will continue with evolving the RESCH framework. This includes the development of new scheduler plugins, such as hierarchical scheduling (for both uni- and multi-core), adjust our recorder to fit with multi-core and implement RESCH for other platforms. In this way, plugin schedulers, recorders etc. can be moved to other platforms (supported by RESCH) without modification. We will also explore the possibilities of doing visualizations of the trace during run-time, rather than offline as in this paper.

References

[1] M. Behnam, T. Nolte, I. Shin, M. Åsberg, and R. J. Bril, "Towards hierarchical scheduling on top of VxWorks," in *Proc. of the OSPERT workshop*, 2008.

[2] M. Åsberg, M. Behnam, F. Nemati, and T. Nolte, "Towards Hierarchical Scheduling in AUTOSAR," in *Proc. of the ETFA conference*, 2009. [Online]. Available: http://www.mrtc.mdh.se/index.php?choice=publications&id=1793

[3] S. Kato, R. Rajkumar, and Y. Ishikawa, "A Loadable Real-Time Scheduler Suite for Multicore Platforms," Technical Report CMU-ECE-TR09-12, 2009. [Online]. Available: http://www.contrib.andrew.cmu.edu/~shinpei/papers/techrep09.pdf

[4] C. Liu and J. Layland, "Scheduling algorithms for multi-programming in a hard-real-time environment," *ACM*, vol. 20, no. 1, pp. 46–61, 1973.

[5] M. Åsberg, T. Nolte, C. M. O. Perez, and S. Kato, "Execution Time Monitoring in Linux," in *Proc. of the W.I.P. session in the ETFA conference*, 2009. [Online]. Available: http://www.mrtc.mdh.se/index.php?choice=publications&id=1792

[6] M. Holenderski, M. M. H. P. van den Heuvel, R. J. Bril, and J. J. Lukkien, "Grasp: Tracing, Visualizing and Measuring the Behavior of Real-Time Systems," in *International Workshop on Analysis Tools and Methodologies for Embedded and Real-time Systems*, July 2010.

[7] H. Thane and H. Hansson, "Using Deterministic Replay for Debugging of Distributed Real Time Systems," in *Proc. of the ECRTS conference*, 2000, pp. 265–272.

[8] H. Thane, D. Sundmark, J. Huselius, and A. Pettersson, "Replay Debugging of Real-Time Systems Using Time Machines," in *Proc. of the IPDPS conference*, 2003, pp. 288–295.

[9] T. Maragria and B. Steffen, editors, "Leveraging Applications of Formal Methods," 1^{st} *International Symposium, ISoLA. Springer*, pp. 140–141, 2004.

[10] D. Faggioli and F. Checconi, "An EDF scheduling class for the Linux kernel," in *Proc. of the Real-Time Linux Workshop*, 2009.

[11] T. Bird, "Measuring Function Duration with Ftrace," in *Proc. of the Japan Linux Symposium*, 2009.

[12] B. Cantrill, M. Shapiro, and A. Leventhal, "Dynamic Instrumentation of Production Systems," in *Proc. of the USENIX conference*, 2004, pp. 15–28.

[13] V. Prasad, W. Colhen, F. Eigler, M. Hunt, J. Keniston, and B. Chen, "Locating System Problems Using Dynamic Instrumentation," in *Proc. of the Ottawa Linux Symposium*, 2005, pp. 49–64.

[14] K. Yaghmour and M. Dagenais, "Measuring and characterizing system behavior using kernel-level event logging," in *Proc. of the USENIX conference*, 2000, pp. 13–26.

[15] M. Desnoyers and M. Dagenais, "The LTTng Tracer: A low impact performance and behavior monitor of GNU/Linux," in *Proc. of the Ottawa Linux Symposium*, 2006, pp. 209–223.

[16] D. Beal, E. Bianchi, L. Dozio, S. Hughes, P. Mantegazza and S. Papacharalambous, "RTAI: Real Time Application Interface," *Linux Journal*, vol. 29, no. 10, 2000.