A Programmable Microkernel for Real-Time Systems

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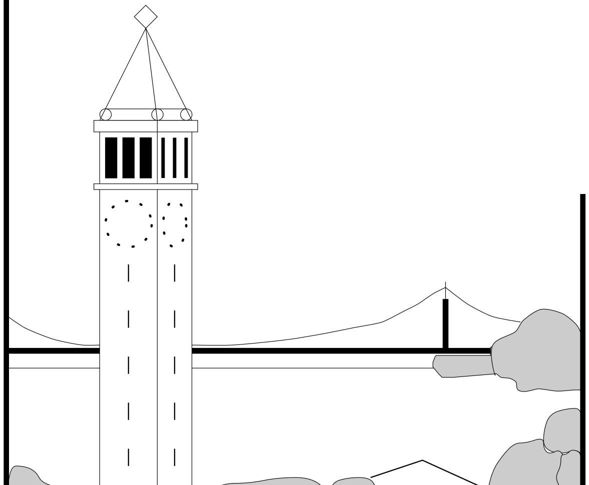

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ABSTRACT

We present a new software system architecture for the implementation of hard real-time applications. The core of the system is a microkernel whose reactivity (interrupt handling) and proactivity (task scheduling) are fully programmable. The microkernel, which we implemented on a StrongARM processor, consists of two interacting virtual machines, a reactive E (Embedded) machine and a proactive S (Scheduling) machine. The system code that runs on the microkernel is partitioned into E and S code. E code manages the interaction of the system with the physical environment: the execution of E code is triggered by environment interrupts, which signal external events such as the arrival of a message or sensor value, and it releases application tasks to the S machine. S code manages the interaction of the system with the processor: the execution of S code is triggered by hardware interrupts, which signal internal events such as the completion of a task or time slice, and it dispatches application tasks to the CPU, possibly preempting a running task. This partition of the system orthogonalizes the two main concerns of real-time implementations: E code refers to environment time and thus defines the reactivity of the system in a hardware- and scheduler-independent fashion; S code refers to CPU time and defines a system scheduler. If both time lines can be reconciled, then the code is called time safe; violations of time safety are handled again in a programmable way, by run-time exceptions. The separation of E from S code permits the independent programming, verification, optimization, composition, dynamic adaptation, and reuse of both reaction and scheduling mechanisms. Our measurements show that the system overhead is very acceptable, generally in the 0.2–0.3% range.

1. INTRODUCTION

In [9], we advocated the E (Embedded) machine as a portable target for compiling hard real-time code. In this paper, we show that the E machine together with a programmable scheduler, which is called S (Scheduling) machine, form a programmable, low-overhead microkernel for real-time systems. We implemented the microkernel on a StrongARM SA-1110 processor and measured the system overhead to lie in the 0.2–0.3% range. The implementation has a very small footprint, namely, 8kB.

The E machine is woken up by external interrupts caused by environment events, such as the arrival of a message on a channel, or the arrival of a new value at a sensor. Once awake, the E machine follows E code instructions to do three things: first, it may run some drivers for managing sensors, actuators, networking, and other devices; second, it may release some application software tasks for execution; third, it may update the trigger queue, which contains pairs of the form (e, a) indicating that the future environment event e will cause an interrupt that wakes up the E machine with its program counter set to the E code address a. Then, the E machine goes back to sleep and relinquishes control of the CPU to the S machine.

The S machine is woken up by the E machine, or by internal interrupts caused by processor events, such as the completion of an application task, or the expiration of a time slice. Once awake, the S machine follows S code instructions to do three things: first, it takes care of processor and memory management, such as context switching; second, it dispatches a single task to the CPU, which may be either an application software task or a special idle task; third, it specifies pairs of the form (i, a) indicating that the future processor event i will cause an interrupt that wakes up the S machine with its program counter set to the S code address a.

The E and S architecture partitions system code into two categories: E code supervises the “logical” execution of application tasks relative to environment events; S code supervises the “physical” execution of application tasks on the given resources. At any time, E code may release several tasks, but if there is only a single CPU, then S code can dispatch at most one released task at a time. In other words, E code specifies the reactivity of an embedded system independent of the hardware resources and the task scheduler, and S code implements a particular scheduler. The scheduler implemented in S code is fully programmable; it may be static or dynamic, preemptive or nonpreemptive. Together, the E and S machines form a programmable microkernel for the execution of hard real-time tasks.

There are several benefits this architecture offers over traditional real-time operating systems.

Real-time predictability of the application behavior. Since E code specifies the reactivity and timing of the system independent of the hardware and scheduler, a change in hardware or scheduler does not affect the real-time behavior of the application. This is especially important in control applications, where both slow-downs and speed-ups may lead to instabilities. By contrast, in a traditional RTOS, the real-time behavior of an application depends on the scheduling scheme, the processor performance, and the system load, which makes both code validation and reuse very difficult. In our setting, timing predictability depends, of course, on the fact that the S code meets the timing requirements specified by the E code. Given worst-case execution times of the application code, this can be checked either statically, by scheduling analysis [10], or at run-time. In the latter case, E code run-time exceptions may be used to handle so-called “time-safety” violations (i.e., missed deadlines) in an explicit, programmable way [9].

Composability of real-time applications. Suppose we want to put two software components, each consisting of E, S,

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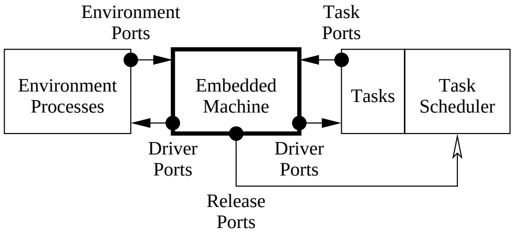

Figure 1: The Interfaces of the Embedded Machine

and application code, on the same hardware. In a traditional RTOS, the combined real-time behavior of both components may differ significantly from their individual behaviors if run in isolation. Not so in our setting, where the E code of both components is always composable, because its execution is synchronous [6], that is, E instructions are executed in "logical zero time" with interrupts turned off. However, the S code of both components constitutes two threads that may or may not be composable: if there is a single CPU, then both S threads are composable provided whenever one thread dispatches an application task, the other thread dispatches the idle task. Composability can, again, be checked either statically or at run-time. In the latter case, a so-called "time-share" violation occurs whenever two S threads attempt to simultaneously control the CPU. Now, S code (rather than E code) run-time exceptions may be used to handle these situations in an explicit, programmable way. This concept can be generalized to multiprocessor hardware, which executes several threads of S code in parallel.

Dynamic adaptation of real-time code. As both E and S code are interpreted, we can dynamically optimize, patch, and upgrade them. A dynamic change in E code modifies the reactivity of a system and can be used, for example, to switch between different modes or contingencies of an embedded controller [9]. Similarly, a dynamic change in S code can be used to optimize or adapt the scheduling scheme without bringing down the system. This permits, in particular, adjustments in the event of hardware failures and thus provides a basis for achieving fault-tolerance without compromising the platform-independent reactivity specification —the E code— of a real-time application.

The real-time microkernel architecture we introduce here provides programmable timing and scheduling services. In this sense, our work relates to other work on microkernels, which typically provide basic thread and interprocess communication services [16, 1, 18, 2]. System services implemented on top of a microkernel have already been shown to perform well, e.g., in [7]. We demonstrate here that high performance is also possible using an even more flexible, programmable microkernel.

The paper is organized as follows. In Section 2, we briefly review the E machine. In Section 3, we introduce the complementary S machine, and in Section 4, we define the combined E and S machines. Section 5 describes our implementation of the programmable microkernel on the StrongARM, and Section 6 tabulates our overhead measurements for many different scenarios. Some of the benefits of this way of architecting a real-time kernel are discussed in the final Section 7.

2. THE EMBEDDED MACHINE

This section is a summary of the E Machine presented in [9]. The E machine is a mediator between physical processes and application software processes: it executes E code, which is system-level machine code that supervises the execution of software processes in relation to physical events.

Interface.

The E machine has two input and two output interfaces as shown in Figure 1.

Environment inputs. The physical processes communicate information to the E machine through *environment ports*, such as clocks and sensors.

Software inputs. The application software processes, called *tasks*, communicate information through *task ports* to the E machine.

Driver outputs. The E machine communicates information to the physical processes and to the tasks by calling system processes, called *drivers*, which write to *driver ports*.

Release outputs. The E machine releases tasks to an external task scheduler for execution by writing to *release ports*.

Logically, the E machine does not need to distinguish between environment and task ports; they are both input ports, while driver and release ports are output ports.

Input Events.

A change of value at an input port, say, a sensor port p_s, is called an *input event*. Every input event causes an interrupt that is observed by the E machine and may initiate the execution of E code. Such an *event interrupt* can be characterized by a predicate called a *trigger*. For example, $p'_s \neq p_s$ is a trigger on p_s, where p'_s refers to the current sensor reading, and p_s refers to the most recent previous sensor reading. A *time trigger* on an environment (clock) port p_c is modeled using a predicate $p'_c = p_c + \delta$ where δ is the number of ticks to wait before the trigger goes off.

Functional Code.

Tasks, drivers, and triggers are functional code that is external to the E machine and must be implemented in some programming language like C. To protect IP, tasks, drivers, and triggers may be given as binary executables to which E code refers through symbolic references. The execution of drivers and tasks is supervised by E code, which monitors input events through triggers.

A task is a piece of preemptive, user-level code, which typically implements a computation activity. A task has no internal synchronization points. A task reads from driver ports and computes on task ports. In favor of a simpler presentation, we assume that the set of ports on which a task operates is fixed. Logically, a task computes a function from its driver and task ports to its task ports provided its ports are not modified when the task is preempted. Each task has a special task port, called *completion port*, which indicates that the task completed execution.

A driver is a piece of system-level code, which typically facilitates a communication activity. A driver may provide sensor readings as arguments to a task, or may load task results into actuators, or may provide task results as arguments to other tasks. A driver may read from any kind of port and write to driver ports. Similarly to tasks, a driver has a fixed set of ports on which it operates. A driver executes in logical zero time, i.e., before the next input event can be observed. In other words, interrupts that implement input events are disabled during the execution of a driver.

A trigger is a piece of system-level code that monitors the occurrences of input events. A trigger may observe environment and task ports (including completion ports), which we

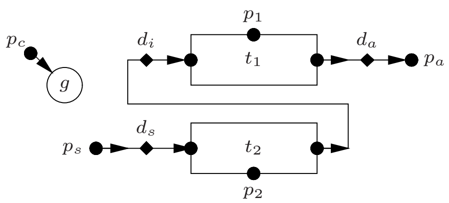

Figure 2: A simplified helicopter flight controller

call its *trigger ports*. Once a trigger is *activated* it is logically evaluated with every input event; an active trigger is *enabled* if it evaluates to true. Similarly to drivers, triggers are evaluated in logical zero time with event interrupts disabled.

E Code. There are essentially three non-control-flow E code instructions. In an actual implementation of the E machine, E code also has control-flow instructions such as conditional and absolute jumps, which we have omitted here.

A `call`(d) instruction initiates the execution of a driver d. As the implementation of d is system-level code, the E machine waits until d is finished before interpreting the next instruction of E code.

A `schedule`(t) instruction releases a task t to run concurrently with other released tasks by emitting a signal to an external task scheduler on the release port of t. Then the E machine proceeds to the next instruction. t does not execute before the E machine relinquishes control of the processor to the scheduler. The `schedule` instruction itself does not order the execution of tasks. If the E machine runs on top of an operating system, the task scheduler may be implemented by the scheduler of the operating system [9]. An alternative implementation of a task scheduler is the S machine of Section 3. The task scheduler is not under control of the E machine; like the physical environment and the underlying hardware, it is external to the E machine and may or may not be able to satisfy the real-time assumptions of E code.

A `future`(g, a) instruction marks the E code at the address a for execution at some future time instant when the trigger g becomes enabled. In order to handle multiple active triggers, a `future` instruction puts the trigger-address pair into a *trigger queue*. With each input event, all triggers in the queue are evaluated. The first pair whose trigger is enabled determines the next actions of the E machine.

An E Code Example

We use as example a simplified version of the control program for a model helicopter built at ETH Zürich [4]. Figure 2 shows the topology of the program: we denote ports by bullets, tasks by rectangles, drivers by diamonds, and triggers by circles. Consider the helicopter in hover mode m. There are two tasks, both implemented in native code: the control task t_1, and the navigation task t_2. The navigation task processes GPS input every 10 ms and provides the processed data to the control task. The control task reads additional sensor data (not modeled here), computes a control law, and writes the result to actuators (reduced here to a single port). The control task is executed every 20 ms. The release port p_1 of t_1 indicates whether t_1 has been released to run. Similarly, p_2 is the release port of t_2.

The data communication requires three drivers: a sensor driver d_s, which provides the GPS data to the navigation task; a connection driver d_i, which provides the result of the navigation task to the control task; and an actuator driver d_a, which loads the result of the control task into the actuator. The drivers may process the data in simple ways (such as type conversion), as long as their WCETs are negligible. There are two environment ports, namely, a clock p_c and the GPS sensor p_s; two task ports, one for the result of each task; and three driver ports —the destinations of the three drivers— including the actuator p_a. Here is a high-level Giotto [8] description of the program timing:

```
mode $m()$ period 20 {
  actfreq 1 do $p_a(d_a)$;
  taskfreq 1 do $t_1(d_i)$;
  taskfreq 2 do $t_2(d_s)$; }
```

The "`actfreq` 1" statement causes the actuator to be updated once every 20 ms; the "`taskfreq` 2" statement causes the navigation task to be invoked twice every 20 ms; etc. The E code generated by the Giotto compiler [10] is shown in Figure 3.

```
$a_0$:  call($d_a$)          $a_1$:  call($d_s$)
        call($d_s$)                  schedule($t_2$)
        call($d_i$)                  future($g, a_0$)
        schedule($t_1$)
        schedule($t_2$)
        future($g, a_1$)
```

Figure 3: E code for the simplified flight controller

The E code consists of two blocks. The block at address a_1 is executed at the beginning of a period, say, at 0 ms: it calls the three drivers, which provide data for the tasks and the actuator, then releases the two tasks to the task scheduler, and finally activates a trigger g with address a_2. When the block finishes, the trigger queue of the E machine contains the trigger g bound to address a_2, and the release ports of the two tasks, t_1 and t_2, are set to ready. Now the E machine relinquishes control, only to wake up with the next input event that causes the trigger g to evaluate to true. In the meantime, the task scheduler takes over and assigns CPU time to the released tasks according to some scheduling scheme. The E machine may observe when a task completes by checking the completion port of the task.

There are two kinds of input events, one for each environment port: clock ticks, and changes in the value of the sensor p_s. The trigger g: $p'_c = p_c + 10$ specifies that the E code at address a_2 will be executed after 10 clock ticks. Logically, the E machine wakes up at every input event to evaluate the trigger, finds it to be false, until at 10 ms, the trigger is true. An efficient implementation, of course, wakes up the E machine only when necessary, in this case at 10 ms. The trigger g is now removed from the trigger queue, and the associated a_2 block is executed. It calls the sensor driver, which updates a port read by task t_2. There are two possible scenarios: the earlier invocation of task t_2 may already have completed with a signal on the completion port of t_2. In this case, the E code proceeds to release t_2 again, and to trigger the a_1 block in another 10 ms, at 20 ms. In this way, the entire process repeats every 20 ms. The other scenario at 10 ms has the earlier invocation of task t_2 still incomplete, i.e., the completion port of t_2 has not yet signaled completion. In this case, the attempt by the sensor driver to overwrite a port read by t_2 causes a run-time exception, called *time-safety violation*. At 20 ms, when ports read by both tasks t_1 and t_2 are updated, and ports written by both t_1 and t_2 are read, a time-safety violation occurs unless both tasks have completed. In other words, an execution of the program is time-safe if the scheduler ensures the following: (1) each invocation of task t_1 at $20n$ ms, for $n \geq 0$, completes by $20n + 20$ ms; (2) each invocation of task t_2 at $20n$ ms completes by $20n + 10$ ms; and (3) each invocation of task t_2 at $20n + 10$ ms completes by $20n + 20$ ms. Therefore, a necessary requirement for time safety is $\delta_1 + 2\delta_2 < 20$, where δ_1 is the WCET of task t_1, and δ_2 is the WCET of t_2. If this requirement is satisfied, then a scheduler that gives priority to t_2 over t_1 guarantees time safety.

The E code implements the Giotto program correctly only if it is time-safe: during a time-safe execution, the navigation task is executed every 10 ms, the control task every 20 ms, and the dataflow follows Figure 2. Thus the Giotto compiler needs to ensure time safety when producing E code. In order to ensure this, the compiler needs to know the WCETs of all tasks and drivers (cf., for example, [5]), as well as the scheduling scheme used by the task scheduler. With this information, time safety for E code produced from Giotto can be checked. However, for arbitrary E code and platforms, such a check is difficult [10], and the programmer may have to rely on run-time exception handling.

Figure 4 shows an execution trace of the E code using an earliest deadline first (EDF) scheduler, which gives priority to tasks with earlier deadlines. The deadlines of the tasks are given as *E code annotations* [9] in the `schedule` instructions (not shown here).

E Code Execution

We define the E code semantics operationally using a pseudo-code description.

Data Structures. An *E program* consists of ports, drivers, tasks, and triggers, as well as E code. The ports are essentially the memory on which the functional code operates. Ports are given as addresses to memory. We use a function $\mathit{Instruction}(a)$ to fetch the E code instruction at the address a. The function $\mathit{Next}(a)$ returns the address of the next instruction; if there is no next instruction, then the function returns $\perp$. This convention is consistent with any control-flow instructions, structured or unstructured, whose choice is of practical importance but entirely orthogonal to the issues discussed here. A *configuration* of an E program consists of the port values (content of memory), a trigger queue of *trigger bindings*, and an E code program counter. A trigger binding (g, a, s) is created by a $\mathtt{future}(g, a)$ instruction that appends it to the trigger queue, where s is the current state of the trigger ports of g. In the future, g will be evaluated with respect to s and the new state of the trigger ports.

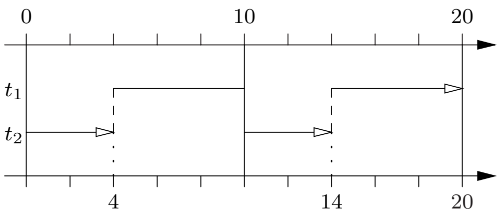

Figure 4: An execution trace of the E code of Figure 3 using an EDF scheduler

Algorithm 1 The Embedded Machine

```
while there is an enabled trigger in $\mathit{TriggerQueue}$ do
  choose the first enabled trigger binding $(g, a, s)$
    and remove it from $\mathit{TriggerQueue}$
  invoke the E code interpreter (Algorithm 2)
    with $\mathit{ProgramCounter} := a$
end while
```

Operational Semantics. The execution of an E program starts with a single trigger binding $(\mathtt{true}, a_0, \emptyset)$ in the trigger queue where a_0 is the address of an initial E code instruction. As soon as the first event interrupt occurs, all event interrupts are disabled and the E machine (Algorithm 1) is invoked (thus it is still possible for low-level interrupts to preempt the E machine, as long as they do not interfere with the triggering mechanism of the machine). Then the E machine scans the trigger queue for enabled trigger bindings. Each enabled trigger binding (g, a, s) is removed from the queue and the E code at the address a is executed by invoking the E code interpreter (Algorithm 2) with the program counter set to a. Initially, the interpreter is invoked with the program counter set to the initial address a_0. The interpreter fetches and executes E code instructions until the program counter is set to $\perp$. In an actual implementation, we use a `return` instruction for which *Next* returns $\perp$.

The E code interpreter implements the E code instructions as follows: a $\mathtt{call}(d)$ instruction executes the code of the driver d. Here, the interpreter may check for a possible time-safety violation by verifiying that all currently released tasks neither read from driver ports written by d nor write to task ports read by d. If there is a violating task t, the interpreter may throw a run-time exception, i.e., not execute the `call` instruction but jump to some other E code that handles the situation [9], e.g., terminates t and executes some other driver. We have implemented run-time exceptions using a compiler-generated $n \times m$ matrix of bits where n is the number of tasks and m is the number of drivers in the E program. The (i, j)th bit in the matrix is 1 if and only if the ith task shares ports with the jth driver. An n-vector of bits keeps track of the released tasks. Then a fast AND operation between the vector and a row of the matrix tells us whether a time-safety violation.

A $\mathtt{schedule}(t)$ instructions releases the task t by emitting a signal on the release port of t. Again, the interpreter may check for a possible time-safety violation by verifiying that all currently released tasks do not share task ports with t. If there is a violating task, the interpreter may either throw a run-time exception, or else release t anyway, which then requires, however, a more sophisticated task scheduler. A $\mathtt{future}(g, a)$ instruction appends a trigger binding (g, a, s)

Algorithm 2 The E Code Interpreter

```
while $\mathit{ProgramCounter} \neq \perp$ do
  $i := \mathit{Instruction}(\mathit{ProgramCounter})$
  if $\mathtt{call}(d) = i$ then
    execute the driver $d$
  else if $\mathtt{schedule}(t) = i$ then
    emit signal on the release port of the task $t$
  else if $\mathtt{future}(g, a) = i$ then
    append the trigger binding $(g, a, s)$ to $\mathit{TriggerQueue}$
    where $s$ is the current state of the trigger ports of $g$
  end if
  $\mathit{ProgramCounter} := \mathit{Next}(\mathit{ProgramCounter})$
end while
```

Algorithm 3 A Task Scheduler

```
if there are released tasks then
    $RunningTask := Schedule(\text{released tasks})$
else
    $RunningTask := \mathsf{idle}$
end if
```

to the trigger queue where s is the current state of the ports monitored by the trigger g. The E code at the address a will be executed as soon as g is enabled.

When there are no more enabled trigger bindings in the trigger queue, the E machine enables the event interrupts and relinquishes control of the processor. At this point, a task scheduler, e.g., Algorithm 3, may take over and schedule the released tasks. The task scheduler may apply any scheduling strategy to choose the next running task including a special idle task. Then the task scheduler relinquishes control of the processor to the running task until the next event interrupt occurs at which the E machine is invoked again.

3. THE SCHEDULING MACHINE

The S machine is a virtual machine that determines the temporal order of task execution: it interpretes S code, which is system-level machine code that dispatches tasks or idles. In the following, we give an overview of the S machine concepts.

Interface. The S machine reads from three input interfaces to determine a running task.

Release inputs. The release of tasks is communicated to the S machine through *release ports*.

Software inputs. The tasks communicate information including their completion to the S machine through *task ports*.

Clock input. An external clock writes to a *clock port* that is read by the S machine to time-slice tasks.

Timeouts. The S machine uses *timeouts* to monitor input events. A timeout is similar to a trigger: it is a predicate over the input ports of the S machine. In particular, we are interested in timeouts of the form $p'_c \geq p_c + \delta$ where p_c is the clock port of the S machine. For readability of the code examples, we abbreviate timeouts to the δ value, e.g., 10ms denotes a timeout $p'_c \geq p_c + 10\text{ms}$. A timeout *expires* if it evaluates to true. We also consider timeouts of the form $release(t)$ where t is a task: $release(t)$ expires if t is released and has not yet completed.

S Code. There are essentially three non-control-flow S code instructions. Again, in an actual implementation of the S machine, S code also has control-flow instructions such as conditional and absolute jumps, which we have omitted here.

A $\texttt{dispatch}(t, m, a)$ instruction resumes the execution of a released task t until the timeout m expires. There are three outcomes: (1) the S machine proceeds to the next instruction if t has already completed but has not yet been released again, or else, (2) the S machine proceeds to the next instruction when t completes provided t completes before the timeout expires, or else (3) the S machine proceeds to the instruction at the address a when the timeout expires before t completes.

An $\texttt{idle}(m)$ instruction makes the S machine idle until the timeout m expires even though there may be released tasks. The S machine proceeds to the next instruction when the timeout expires.

```
a0:  dispatch(t2)
     dispatch(t1)
     idle(release(t2))
     dispatch(t2)
     idle(release(t1))
     fork(a0)
```

Figure 5: Synchronous S code

A $\texttt{fork}(a)$ instruction marks the S code at the address a for execution in parallel to the S code that follows the instruction. The S code at a is a new *S thread* of execution. The running *thread instances* are kept in a *thread set* from which instances are chosen non-deterministically to execute. If multiple threads dispatch more than a single task at any instant the S machine throws a run-time exception, called *time-share violation*.

We use $\texttt{dispatch}(t)$ to abbreviate $\texttt{dispatch}(t, \mathsf{false}, a)$ as well as $\texttt{dispatch}(t, m)$ to abbreviate $\texttt{dispatch}(t, m, a)$, where a is the address of the next instruction.

S Code Examples

We present several S code examples that schedule the tasks t_1 and t_2 of Section 2 in different ways. Recall that t_1 is released once every 20ms while t_2 is released once every 10ms. Figure 5 shows S code that dispatches t_1 and t_2 as follows: the S machine starts executing the S code at the address a_0 after both tasks have been released for the first time. t_2 is dispatched first. When t_2 completes, t_1 is dispatched. When t_1 completes, the S machine idles until t_2 is released again. Then t_2 is dispatched again until t_2 completes at which point the S machine idles until t_1 is released again. Then the S machine forks back to the S code at a_0. Since there is no S code following the $\texttt{fork}(a_0)$ instruction, the current thread is terminated. Even in this case a fork is different than a jump to a_0 because, upon forking, the new thread instance is assigned the current clock value as its *reference time* for timeouts. This will be explained in more detail below.

Figure 6 shows an execution trace of the S code. The S code guarantees the time-safe execution of the E code in Figure 3 if both tasks t_1 and t_2 complete within 10ms, i.e., if the tasks are never preempted by the release of a task. We call S code *synchronous* if, in any execution of the S code, all released tasks always complete before another task is released.

In contrast, the S code in Figure 7 allows the task t_1 to be preempted by the release of t_2, e.g., the E machine, and then the execution of t_2 itself. At startup, t_2 executes until completion. Then the $\texttt{dispatch}(t_1, release(t_2))$ instruction

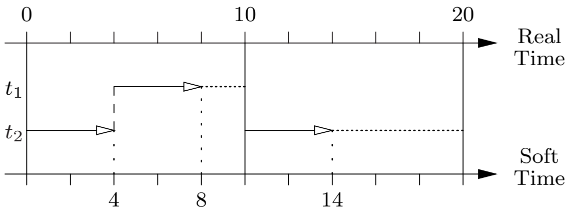

Figure 6: An execution trace of the S code of Figure 5

```
a0:  dispatch(t2)
     dispatch(t1, release(t2), a1)
     idle(release(t2))
a1:  dispatch(t2)
     dispatch(t1)
     idle(release(t1))
     fork(a0)
```

Figure 7: Preemptive S code

executes t_1 until either t_1 completes or t_2 is released again. If t_2 is released before t_1 completes, t_1 is preempted and the S machine continues executing the S code at the address a_1. Here, t_2 is dispatched until completion before t_1 resumes its execution. If, however, t_1 would have completed before t_2 was released, the dispatch(t_1) instruction following the instruction at a_1 would have no effect on t_1. The execution trace of the S code corresponds to the execution trace of the E code using an EDF scheduler as shown in Figure 4. Thus the S code describes an EDF schedule for the E code. We call S code *preemptive* if, in any execution of the S code, tasks may be preempted by (1) the release and (2) the execution of other tasks.

The S code in Figure 8 again allows the task t_1 to be preempted by the release of t_2 but then resumes the execution of t_1 instead of executing t_2. If t_1 does not complete before t_2 is released again, t_1 is dispatched resuming its execution before t_2 is dispatched. Figure 9 shows an execution trace of the S code. We call S code *non-preemptive* if, in any execution of the S code, tasks are at most preempted by the release but not by the execution of other tasks. Synchronous S code is non-preemptive but not vice versa.

In Section 6, we will show experimental evidence that executing E and S code of different classes occurs at different administrative overhead because of scheduling and context switching. As shown in Figure 10, it turns out that synchronous S code causes less overhead than the other classes because there is neither dynamic scheduling nor context switching required. However, the drawback of synchronous S code is that (1) tasks have to compute faster than the basic unit of time, i.e., at least as fast as the most-frequent system activity, and (2) system utilization may be poor. At the other end, there is E code using a task scheduler instead of S code. Depending on the scheduler, tasks may be preempted at any time and system utilization may reach 100%, at the cost of scheduling and context switching overhead. Preemptive S code can reduce the overhead because fewer scheduling decisions are made at run-time. However, context switching is still necessary. Non-preemptive S code can reduce the overhead even further because context switching is only necessary between system and tasks but not between tasks. Generating non-preemptive S code, on the other hand, is an NP-hard problem [12, 3] and can thus only be approximated.

The S code in Figure 11 enables a time-sliced execution of the tasks t_1 and t_2. Here, a time slice is 5ms long. First, t_2 is dispatched for 5ms, then t_1 for 5ms. After 10ms, t_2 is dispatched again for 5ms, then t_1 for 5ms. The S code guarantees time safety provided t_1 has a WCET of 10ms and t_2 has a WCET of 5ms. An execution trace of the S code is shown in Figure 12. Executing the S code in Figure 13 results in the same execution trace. Here, the S code forks two threads: the S code at the address a_1 dispatches t_1 whereas the S code at the address a_2 dispatches t_2. Both tasks are dispatched in disjoint time slots. We say that the S code is *time-sharing*. Thus a scheduler may generate S code in a modular fashion with one thread of S code for each task that needs to be dispatched.

```
a0:  dispatch(t2)                     a1:  dispatch(t1)
     dispatch(t1, release(t2), a1)         dispatch(t2)
     idle(release(t2))                     idle(release(t1))
     dispatch(t2)                          fork(a0)
     idle(release(t1))
     fork(a0)
```

Figure 8: Non-preemptive S code

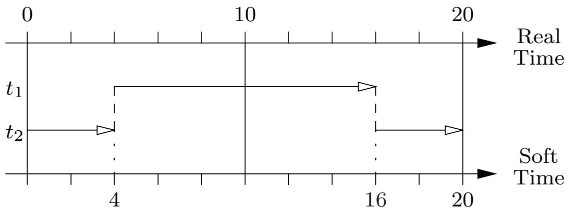

Figure 9: An execution trace of the S code of Figure 8

The S code in Figure 14 demonstrates multi-processor S code as it is generated by a prototypical Giotto compiler that targets distributed architecures. Suppose there are two hosts h_1 and h_2 where each host runs an S machine. The hosts are connected by an Ethernet network. Moreover, there is a clock synchronization service running between both S machines. h_1 executes the S code at the address a_1. h_2 executes the S code at the address a_2 in a synchronized fashion with h_1. Both hosts also execute different subsets of the E code of Figure 3. However, here it is only important that the intertask driver d_i of Figure 2 will be invoked by h_1. Recall that the task t_1 receives the output of the task t_2 at a rate of 20ms when d_i is invoked. Thus the output of the second invocation of t_2 must be sent across the network after the invocation completed and before the 20ms period is finished. The S code on h_2 dispatches a task s_{21} that sends the output of t_2 across the network within the 15-20ms time slot. The S code on h_1 dispatches at the same time a task r_{21} that receives the output. Figure 15 shows an execution trace of the distributed system. Note that another interesting target platform for this kind of S code is the time-triggered architecture [15].

S Code Execution

We define the S code semantics operationally using a pseudocode description.

Data Structures. An *S program* consists of ports, tasks, and timeouts, as well as S code. Similar to E code, we use a function *Instruction*(a) to fetch the S code instruction at the address a and a function *Next*(a) that returns the address

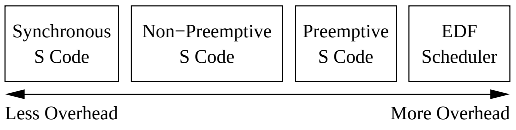

Figure 10: The relative overhead for executing different classes of S code and an EDF scheduler

```
$a_0$:  dispatch($t_2, 5ms$)
        idle($5ms$)
        dispatch($t_1, 10ms$)
        idle($10ms$)
        fork($a_0$)
```

Figure 11: Time-sliced S code

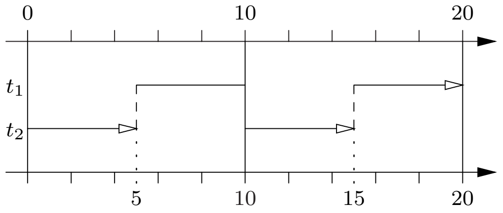

Figure 12: An execution trace of the S code of Figure 11

```
$a_0$:  fork($a_2$)
$a_1$:  idle($5ms$)                  $a_2$:  dispatch($t_2, 5ms$)
        dispatch($t_1, 10ms$)                idle($10ms$)
        idle($10ms$)                         fork($a_2$)
        fork($a_1$)
```

Figure 13: Multi-threaded and time-sliced S code

of the next instruction. A *configuration* of an S program consists of the port values, a set of thread instances called the thread set, a *reference time*, a *running task*, and an S code program counter. The reference time is the clock value at the instant when the current thread was started. The running task is the currently dispatched task. A thread instance is of the form (t, b, m, a, s), which is created by the three S code instructions. t is either a task or the special idle task for which b is $\bot$. Otherwise, b is the address from which the S machine continues executing when t completes before the timeout m expires. When m expires before t completes, we say that the thread instance is *enabled* and the S machine continues executing S code at the address a. The clock value s is the reference time at which the thread instance was started by a fork instruction.

```
$a_1$:  dispatch($t_1, 5ms$)         $a_2$:  dispatch($t_2, 5ms$)
        idle($10ms$)                         idle($10ms$)
        dispatch($t_1, 15ms$)                dispatch($t_2, 15ms$)
        idle($15ms$)                         idle($15ms$)
        dispatch($r_{21}, 20ms$)             dispatch($s_{21}, 20ms$)
        idle($20ms$)                         idle($20ms$)
        fork($a_1$)                          fork($a_2$)
```

Figure 14: Multi-processor S code

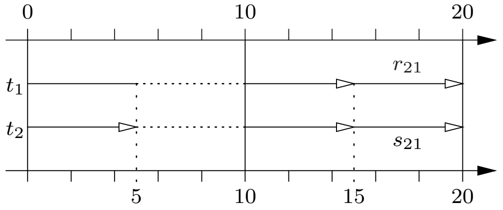

Figure 15: An execution trace of the S code of Figure 14

Algorithm 4 The Scheduling Machine

```
$YieldToTask$ := false
while ¬ $YieldToTask$ do
  if there is a completed task $t$ in $ThreadSet$ then
    choose a thread instance $(t, b, m, a, s)$
      and remove it from $ThreadSet$
    invoke the S code interpreter (Algorithm 5)
      with $ReferenceTime := s$
      and $ProgramCounter := b$
  else if there is an enabled thread in $ThreadSet$ then
    choose an enabled thread instance $(t, b, m, a, s)$
      and remove it from $ThreadSet$
    invoke the S code interpreter (Algorithm 5)
      with $ReferenceTime := s$
      and $ProgramCounter := a$
  else
    $YieldToTask$ := true
  end if
end while
if there is a task $t \neq$ idle in $ThreadSet$ then
  $RunningTask := t$
else
  $RunningTask$ := idle
end if
```

Operational Semantics. The execution of an S program starts with a single thread instance (idle, $\bot$, true, a_0, 0) in the thread set where a_0 is the address of an initial S code instruction. As soon as the first event interrupt occurs, all event interrupts are disabled and the S machine (Algorithm 4) is invoked. Then the S machine scans the thread set for completed tasks and enabled thread instances. Each thread instance (t, b, m, a, s) containing a completed task t (or an expired timeout m) is removed from the thread set and the S code at the address b (a) is executed by invoking the S code interpreter (Algorithm 5) with the program counter set to b (a). Thus, similar to the E code interpreter, the S code interpreter is initially invoked with the program counter set to the initial address a_0.

The S code interpreter implements the S code instructions as follows: a dispatch(t, m, a) instruction creates a thread instance (t, b, m, a, s) where b is the address of the next instruction and s is the reference time at which the current thread was started. Here, the interpreter may check for a possible time-share violation by verifying that all thread instances in the thread set contain the special idle task. If there is a thread instance with a task in the thread set, the

Algorithm 5 The S Code Interpreter

```
$YieldToThreads$ := false
while $ProgramCounter \neq \bot$ and ¬ $YieldToThreads$ do
  $i := Instruction(ProgramCounter)$
  if dispatch$(t, m, a) = i$ then
    insert the thread instance
      $(t, Next(ProgramCounter), m, a, ReferenceTime)$
      into $ThreadSet$
    $YieldToThreads$ := true
  else if idle$(m) = i$ then
    insert the thread instance
      (idle, $\bot$, $m$, $Next(ProgramCounter)$, $ReferenceTime$)
      into $ThreadSet$
    $YieldToThreads$ := true
  else if fork$(a) = i$ then
    insert the thread instance (idle, $\bot$, true, $a$, $s$) into
      $ThreadSet$ where $s$ is the current clock value
  end if
  $ProgramCounter := Next(ProgramCounter)$
end while
```

```
$a_0$:  call($d_a$)          $a_1$:  call($d_s$)
        call($d_s$)                  schedule($t_2$)
        call($d_i$)                  future($g, a_0$)
        schedule($t_1$)              dispatch($t_2$)
        schedule($t_2$)
        future($g, a_1$)
        dispatch($t_2$)
        dispatch($t_1$)
```

Figure 16: System code implementing the E code of Figure 3 interacting with the S code of Figure 5

interpreter may throw a run-time exception, i.e., not execute the violating `dispatch` instruction but jump to some other S code that handles the situation. An `idle`(m) instruction creates a thread instance (idle, $\perp, m, a, s$) where a is the address of the next instruction and s is the reference time at which the current thread was started. A `fork`(a) instruction creates an already enabled thread instance (idle, $\perp$, true, a, s) in the thread set where s is the current time. Thus the S code at a will be executed in the current instant as soon as the interpreter finishes executing the S code that follows the `fork` instruction. When there are no more completed tasks or enabled thread instances in the thread set, the S machine chooses a running task, enables the event interrupts and relinquishes control of the processor to the running task until the next event interrupt occurs at which the S machine is invoked again. If the S code is time-sharing, there is at most a single task in the thread set that can become the running task. Otherwise, the running task is the special idle task.

4. INTERACTING E AND S MACHINES

We discuss an implementation of interacting E and S machines. Instead of implementing both machines side-by-side, we propose an implementation that integrates the E and S machine into a single machine, which constitutes the core of the programmable microkernel. An important aspect of an integrated implementation is to determinize correctly the logical order in which the E and S machine are invoked. For example, logically, the E machine should be invoked before the S machine when an E code trigger is enabled at the same time instant when an S code timeout expires because the E code may release tasks that require immediate scheduling service from the S code. An integrated E and S machine interprets *system code* that may consist of E code and S code instructions. Figure 16 shows an example of system code that implements the E code of Figure 3 interacting with the S code of Figure 5. Logically, after the E code at the address a_0 in Figure 3 has been executed, the S machine is invoked to execute the S code at the address a_0 in Figure 5. Operationally, instead of executing E and S code in different programs, we append the S code to the E code as shown in the example and use the integrated machine. For example, after executing the `future`(g, a_1) instruction, the machine immediately proceeds to the `dispatch`(t_2) instruction, creates a thread instance with the task t_2, and then executes t_2. Logically, the E machine terminates and is then followed by an invocation of the S machine, which evaluates the release ports to determine the release status of the tasks. System code is a more succinct representation of this behavior. Note that the `idle` and `fork` instructions in the S code of Figure 5 are not necessary in the system code of Figure 16.

Algorithm 6 The Event Loop of the Integrated Machine

```
$YieldToTask$ := false
while ¬ $YieldToTask$ do
  if there is a completed task $t$ in $ThreadSet$ then
    choose a thread instance $(t, b, m, a, s)$
      and remove it from $ThreadSet$
    invoke the system code interpreter
      with $ReferenceTime := s$
      and $ProgramCounter := b$
  else if there is an enabled trigger in $TriggerQueue$ then
    choose the first enabled trigger binding $(g, a, s)$
      and remove it from $TriggerQueue$
    invoke the system code interpreter
      where $ReferenceTime$ is the current clock value
      and $ProgramCounter := a$
  else if there is an enabled thread in $ThreadSet$ then
    choose an enabled thread instance $(t, b, m, a, s)$
      and remove it from $ThreadSet$
    invoke the system code interpreter
      with $ReferenceTime := s$
      and $ProgramCounter := a$
  else
    $YieldToTask$ := true
  end if
end while
if $ThreadSet \neq \emptyset$ then
  if there is a task $t \neq$ idle in $ThreadSet$ then
    $RunningTask := t$
  else
    $RunningTask$ := idle
  end if
else
  invoke the task scheduler (Algorithm 3) if present
end if
```

Data Structures. We need the following data structures for the integrated implementation. A *system program* consists of ports, drivers, tasks, triggers, and timeouts, as well as system code. A *configuration* of a system program consists of a system program, a trigger queue, a thread set, a reference time, a running task, and a system code program counter.

Implementation. Algorithm 6 implements the integrated E and S machine. Since there are instants at which both the E machine and the S machine must be invoked, event interrupts are evaluated in the following, deterministic order: (1) task completion in the thread instances first, then (2) enabled triggers in the trigger bindings, and finally (3) expired timeouts in the thread instances. There are two motivations for this particular order. (1) before (2): task completion may require special handling, e.g., through driver calls in system code, prior to executing any other system code; and (2) before (3): enabled triggers may invoke system code that releases tasks, which require scheduling service from system code. Note that the integrated E and S machine may also use a task scheduler (Algorithm 3) to schedule released tasks if there are no thread instances in the thread set in order to support the execution of E code without S code.

The integrated E and S machine uses a system code interpreter, which can execute any E and S code. The interpreter implements a straightforward merge of the E and S code interpreters. As a consequence, system code is in fact more general than interacting E and S code. For example, a thread written in system code, as opposed to S code, may call drivers, which may actually be useful in practice. However, we have presented E and S code separately because both types of code address equally important but orthogonal aspects of real-time systems. System code is an efficient representation of interacting E and S code but generating system code may still benefit from keeping the logical difference of E and S code in mind.

5. MICROKERNEL IMPLEMENTATION

In this section, we discuss the implementation of the programmable microkernel on a StrongARM SA-1110 processor running at 206MHz. We use a motherboard that was designed originally at ETH Zürich as part of a model helicopter project and is now available from *weControl*, an ETH spin-off company. The board was already used to implement a Giotto-based flight controller [13] for the helicopter. The implementation is a patch of the custom-designed real-time operating system HelyOS [17] written in Oberon [19]. We have implemented a number of optimizations that exploit features of the processor and the compiler. We discuss the architecture-dependent aspects of the implementation at the end of this section.

Architecture-Independent Implementation

We present pseudo-code descriptions of the Oberon code that embeds the integrated E and S machine (Algorithm 6) and the system code interpreter into the microkernel.

Data Structures. We use the following data structures. The *system state* consists of two parts: (1) a system program and its configuration; and (2) a *kernel state*, which consists of a *preempted task*, a *processor context*, and a set of *task instances* called *task set*. The running task becomes the preempted task when an event interrupt occurs that preempts the running task. The processor context is a set of variables that contain the values of all registers of the processor. Typically, the stack and frame pointers as well as the processor status are stored in reserved registers. A task instance consists of a task and a processor context. For efficiency, all sets and queues are implemented by fixed-size arrays.

Implementation. At system startup, the bootstrap program (Algorithm 7) initializes the microkernel as follows: first, the initial task instance of the special idle task (Algorithm 8) is inserted into the task set. Then the trigger queue, thread set, and system program are initialized to be empty. The auxiliary system code and run variables are used by the idle task to receive system code from the host computer. Next, a HelyOS I/O handler is bound to an input and an output interrupt. We maintain two cyclic buffers that decouple the microkernel from the hardware: (1) an input buffer that is filled by the I/O handler when data is received from the host computer (on a serial link); and (2) an output buffer that is emptied by the I/O handler, which sends the content to the host computer. The next step of the bootstrap program is to bind the event interrupt handler (Algorithm 9) that invokes the integrated E and S machine to the system clock interrupt. We have not yet bound the event interrupt handler to other interrupts although this is possible. Finally, all interrupts are enabled and the idle task is invoked. The idle task only returns when a shutdown command from the host computer was received. Then all interrupts are disabled and the system is shutdown. Note that during system operation the I/O interrupts remain enabled even when the microkernel is running achieving nanosecond-latency I/O.

Algorithm 7 The Bootstrap Program

```
disable all interrupts
add $(\mathsf{idle}, \mathit{InitialContext}(\mathsf{idle}))$ to $\mathit{TaskSet}$
$\mathit{TriggerQueue} := \bot$; $\mathit{ThreadSet} := \emptyset$
$\mathit{SystemProgram} := \bot$; $\mathit{SystemCode} := \bot$
$\mathit{Run} := \mathsf{true}$
bind HelyOS I/O handler to I/O interrupts
bind the event interrupt handler (Algorithm 9)
  to system clock interrupt
enable all interrupts
invoke idle task (Algorithm 8)
disable all interrupts
shutdown system
```

The idle task checks in a while loop whether commands from the host computer were received and sends logging information generated by the microkernel and the tasks to the host computer. Algorithm 8 shows only two commands: (1) the switchcode command announces system code sent from the host computer; and (2) the shutdown command terminates the idle task and shuts down the system. The host computer sends system code along with the switchcode command. The idle task receives the code, and stores it if it passes an integrity check of opcodes and arguments. In Section 7 we discuss various other integrity checks as well as more potential commands for the microkernel. The idle switches the system program executed by the microkernel to the received system code as soon as a *safe* instant is reached. Here, a safe instant is any instant when all tasks have completed. Other, less trivial choices are possible.

Now, suppose that the idle task is running and an event interrupt (system clock tick) occurs. The event interrupt handler (Algorithm 9) is invoked, which immediately disables the event interrupts and then saves the registers in the processor context variables. Then the running task is saved as the preempted task before the event loop of the integrated machine checks for system code to be executed and determines the next running task. If the preempted task is again chosen to be the next running task, the registers are restored from the processor context variables and the handler returns from the interrupt. For this (often frequent) case, we demonstrate below in an architecture-dependent way that saving and restoring the processor context can entirely be avoided.

If the next running task is different from the preempted task, the preempted task instance in the task set is updated

Algorithm 8 The Idle Task

```
while $\mathit{Run}$ do
  receive $\mathit{Command}$ from host
  if $\mathit{Command} = \mathtt{switchcode}$ then
    receive $\mathit{SystemCode}$ from host
    if checking $\mathit{SystemCode}$ integrity fails then
      $\mathit{SystemCode} := \bot$
    end if
  else if $\mathit{Command} = \mathtt{shutdown}$ then
    $\mathit{Run} := \mathsf{false}$
  end if
  if $\mathit{SystemCode} \neq \bot$ then
    disable event interrupts
    if $\mathit{TaskSet} = \{(\mathsf{idle}, c)\}$ then
      $\mathit{SystemProgram} := \mathit{SystemCode}$; $\mathit{SystemCode} := \bot$
      $\mathit{TriggerQueue} := \langle(\mathsf{true}, 0, \emptyset)\rangle$; $\mathit{ThreadSet} := \emptyset$
    end if
    enable events interrupts
  end if
  send logging information to host
end while
```

Algorithm 9 The Event Interrupt Handler

```
disable event interrupts
save registers in $ProcessorContext$
$PreemptedTask := RunningTask$
invoke the event loop (Algorithm 6)
if $RunningTask \neq PreemptedTask$ then
   update ($PreemptedTask, ProcessorContext$) in $TaskSet$
   if there is a $RunningTask$ instance in $TaskSet$ then
      get ($RunningTask, ProcessorContext$) from $TaskSet$
   else
      $ProcessorContext := InitialContext(RunningTask)$
      add ($RunningTask, ProcessorContext$) to $TaskSet$
      set stack pointers according to $ProcessorContext$
      leave interrupt handler by invoking $RunningTask$
        with enabled event interrupts
      disable event interrupts
      remove $RunningTask$ instance from $TaskSet$
      invoke the event loop (Algorithm 6)
      invoke the completion handler (Algorithm 10)
      // never returns here
   end if
end if
restore registers from $ProcessorContext$
return from interrupt with enabled event interrupts
```

with the current processor context. Then, if the next running task has previously been preempted, its processor context is retrieved from the task set, the registers are restored, and the handler returns from the interrupt. Otherwise, if the next running task has not been dispatched before, the processor context variables are initialized for the task and an initial task instance is created in the task set. Then, the stack pointers are set according to the processor context variables before the handler leaves the interrupt by invoking the task. When the task completes, the processor returns to the event interrupt handler with an empty stack where the event interrupts are disabled before its task instance is removed from the task set. This part of the event interrupt handler is in fact not handling a processor interrupt anymore. Next, the event loop of the integrated machine is invoked to execute system code and to determine the next running task. Once the machine is finished, the completion handler (Algorithm 10) is invoked to dispatch the task. The completion handler is similar to the event interrupt handler except that context switching is explicit rather than upon returning from a processor interrupt.

Architecture-Dependent Optimization

We describe an architecture-dependent optimization that reduces the number of context switches when the microkernel is invoked by an event interrupt. The StrongARM SA-1110 has 16 registers R0–R15 of which R0-R11 are general purpose registers and R12–R15 are reserved for system-specific use such as the stack and frame pointers. A context switch on the StrongARM requires to save all 16 registers to memory and then restore the registers from memory. The processor can operate in six different modes. In our implementation we use three of the six modes: (1) the HelyOS I/O handler runs in the IRQ mode; (2) the microkernel runs in the fast interrupt mode (FIQ); and (3) the tasks (including the idle task) run in the supervisor mode (SVC). The important difference among these modes is that the FIQ mode, unlike the IRQ and SVC modes, has a private set of registers R8–R15 that cover the registers R8–R15 of the other modes when the processor is in the FIQ mode. Thus a context switch in the FIQ mode can be avoided if the FIQ handler, i.e., the microkernel, only uses the registers R8–R15 and if the FIQ handler decides that, upon leaving the FIQ mode, the processor should resume the execution from where it was preempted.

Algorithm 10 The Completion Handler

```
if there is a $RunningTask$ instance in $TaskSet$ then
   get ($RunningTask, ProcessorContext$) from $TaskSet$
   restore registers from $ProcessorContext$
   switch context and enable event interrupts
   // never returns here
else
   $ProcessorContext := InitialContext(RunningTask)$
   add ($RunningTask, ProcessorContext$) to $TaskSet$
   invoke $RunningTask$ with enabled event interrupts
   disable event interrupts
   remove $RunningTask$ instance from $TaskSet$
   invoke the event loop (Algorithm 6)
   invoke the completion handler (Algorithm 10)
   // never returns here
end if
```

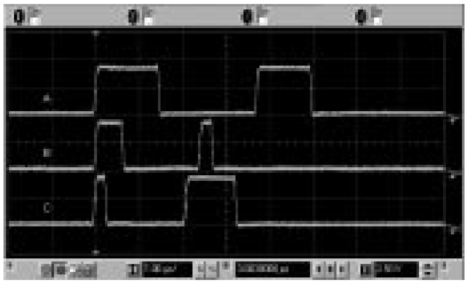

Figure 17: Context Switching on an Oscilloscope

In order to implement the optimization four modifications of our code were required: (1) we modified the Oberon compiler to support a procedure annotation that restricts the choice of registers the compiler can use to compile an annotated procedure; then, (2) we annotated the microkernel and compiled it to machine code that only uses the R8–R15 registers. Most importantly, drivers called by the microkernel are excluded from this restriction because (3) we modified the system code interpreter to save all 16 registers before a driver is called. This can easily be generalized such that the interpreter distinguishes restricted from unrestricted drivers. Finally, (4) we changed the event interrupt handler (Algorithm 9) as follows: we removed the code at the beginning and the end of the handler that saves and restores the registers in the processor context. Then, we inserted the code that saves the registers right before the processor context is needed to update the preempted task instance in the task set. Finally, we inserted the code that restores the registers right after the next running task instance is retrieved from the task set. Now, when an event interrupts occurs, the processor enters the FIQ mode and invokes the event interrupt handler, which first disables the event interrupts. Then, the handler immediately saves the running task as the preempted task and invokes the event loop of the integrated machine without saving any of the registers in the processor context. When the event loop is finished and the next running task and the preempted task are equivalent, the handler immediately returns from the interrupt without the need of restoring any of the registers. Otherwise, the registers are saved and then restored for the next running task.

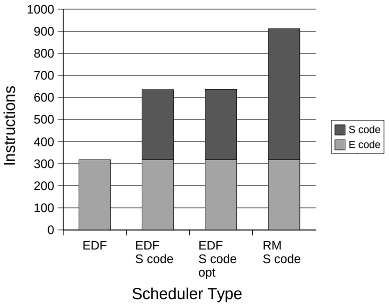

Figure 18: E and S code size for 100 tasks

Figure 17 shows the performance gain of the optimization. The measurement (A) shows an invocation of the event interrupt handler without the optimization and (B) with the optimization. An invocation begins with the first rising edge and ends with the second falling edge. The time between the two pulses is the time it takes the microkernel to determine in the event loop whether system code needs to be executed. Here, system code is not executed. The mean time it takes to go through the event loop with a single trigger binding in the trigger queue and a single thread instance in the thread set is around 2μs in our experiments. The first pulse of (A) shows the time (1.26μs) it takes to set the next timer interrupt and to save the registers. Each pulse includes a 200ns I/O overhead to toggle from zero to one and back, which we exclude in the numbers. Thus the actual execution time of the handler is 400ns shorter than shown in the Figure. The second pulse of (A) shows the time (1.05μs) it takes to restore the registers. Thus the minimum execution time to handle a timer interrupt without the optimization is 4.31μs. The first pulse of (B) shows the time (0.43μs) it takes to set only the next timer interrupt while the second pulse of (B) shows only the time (200ns) to toggle from zero to one and back. Thus the minimum execution time to handle a timer interrupt with the optimization is 2.43μs. The measurement (C) shows a task completion followed by an invocation of the microkernel that determines a next running task that requires initializing the processor context. The first pulse of (C) shows only the time (200ns) it takes to toggle from zero to one and back while the second pulse of (C) shows the time (0.94μs) it takes to initialize the processor context and load the registers. Thus the minimum time it takes to complete the execution of a task and to determine the next running task (using S code) is 2.94μs. Here, the optimization has no effect.

6. MICROKERNEL BENCHMARKS

The binary code size of the programmable microkernel is 8kB, which includes the I/O handling code of HelyOS. Thus, due to its small size, the microkernel can even be used on small embedded devices with limited CPU and memory resources. For the benchmarks, the microkernel is invoked at 1kHz. Thus tasks are preempted every 1ms, called the *microkernel period*. We evaluated the microkernel on four periodic, non-harmonic task sets with 4, 10, 50, and 100 tasks. Each set consists of four equally large task groups with 16.66Hz, 33.33Hz, 50Hz, and 100Hz tasks The task sets are described by E code. There is an E code block for each instant in the hyperperiod of the task sets at which tasks are released.

System Code Size. Each task set is scheduled using four different methods: (1) an EDF scheduler; (2) preemptive (EDF) S code generated by the EDF scheduler; (3) non-preemptive (EDF) S code; and (4) preemptive (RM) S code generated by a rate-monotonic (RM) scheduler. We have implemented the EDF scheduler as default task scheduler of the microkernel. The non-preemptive (EDF) S code was generated from the preemptive (EDF) S code by reordering task execution, which was not always possible. The preemptive (RM) S code was generated such that at each instant all tasks are dispatched in the order of decreasing frequencies.

In order to avoid WCET analysis of task code, we generated all S code at run time and implemented the tasks without branching such that the actual execution times are close to the WCETs. The task code consists of integer operations (the StrongARM has no FPU) and I/O operations in order to visualize the task behavior on an oscilloscope. For each task set we used three different task implementations with short, medium, and long execution times.

We ran a total of 48 different test cases. For each test, we measured (per invocation of the microkernel): (1) the overall system code (microkernel) execution time as well as its parts: (2) the E code execution time; (3) the S code execution time; (4) the EDF scheduler execution time. We also measured the total CPU utilization (U) and counted the number of task preemptions (P) per hyperperiod (60ms) as well as the number of S code and E code instructions. For the time measurements, we used the internal 3.6864Mhz OS timer of the StrongARM. The test results are summarized in Table 1, 2, and 3.

Figure 18 shows the system code size (E code and S code) for 100 tasks that are scheduled according to the four different scheduling methods (the E code is always the same). The preemptive (RM) S code is larger than the (EDF) S code because each task is dispatched according to its frequency but independently of its execution time. In other words, tasks may have already completed before they are (unnecessarily) dispatched again.

E code Execution Overhead. Figure 19 shows E code execution times with respect to the number of tasks released by the E code. Independently of the task scheduling method, the increase of E code execution times is linear in the number of tasks because the number of E code instructions grows in a linear fashion with the number of tasks.

Scheduling Overhead. Figure 20 shows the scheduling overhead of the microkernel. The EDF scheduler maintains a sorted list to determine the next running task. The S code

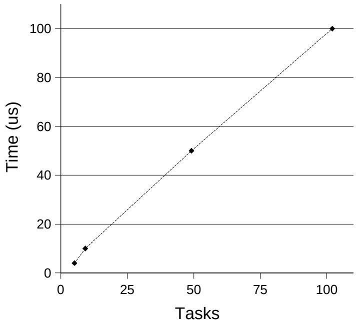

Figure 19: E code execution overhead

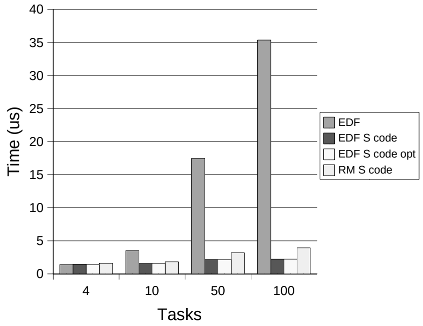

Figure 20: Scheduling overhead (EDF scheduling and S code execution)

we consider here, on the other hand, determines the next running task directly through current control locations in S code, which explains the near constant growth. Note that more efficient implementations of our EDF scheduler using multiple lists [20] are possible but do not achieve S code performance. The S code shown here trades space for time although the S code size even for 100 tasks is still small. The preemptive (RM) S code is slower than other S code because the (RM) S code dispatches more often already completed tasks. The execution times of preemptive and non-preemptive (EDF) S code for 50 and 100 tasks are equivalent since preemptions do not occur in both cases.

System Overhead. Figure 21 shows the total system overhead in terms of system code execution times (E code and S code execution times plus the execution time of the EDF scheduler when used). With S code, it is possible to keep the system overhead under 10μs even for 100 tasks.

CPU Utilization. Figure 22 shows the CPU utilization with different scheduling methods. CPU utilization improves with the number of tasks when switching from the EDF scheduler to preemptive (EDF) S code. With 100 tasks, S code performs 35% better than the traditional EDF scheduler (51% utilization versus 78% utilization).

7. CAPABILITIES

We have presented a new software system architecture for the implementation of hard real-time applications. The core of the system is a programmable microkernel that executes system-level functionality written in system code, which consists of E and S code. Semantic structure and predictability are the key properties of system code that form the foundation of the microkernel's capabilities. E and S code address semantically orthogonal issues. E code defines the reactivity of the system with respect to the physical environment while S code defines application task scheduling. System code is dynamic in the sense that it can be replaced, modified, extended, and communicated at run-time. Modifying an E code portion of system code changes the reactive behavior of the system while modifying the S code part changes the scheduling scheme. The semantic structure of system code enables the analysis and composition of real-time programs on the system level. System code does not necessarily replace traditional real-time scheduling technology. Partial system code can be complemented at run-time, e.g., by a real-time scheduler that either executes application tasks not handled by system code, or generates the missing system code on-the-fly. Predictability and composability of system code enables portability and mobility of real-time programs.

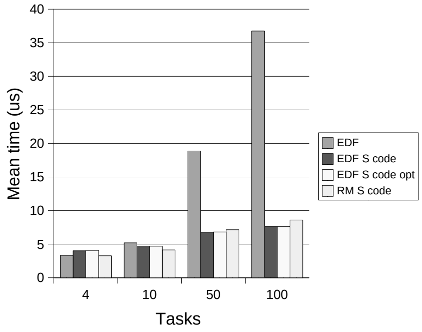

Figure 21: E and S code execution overhead

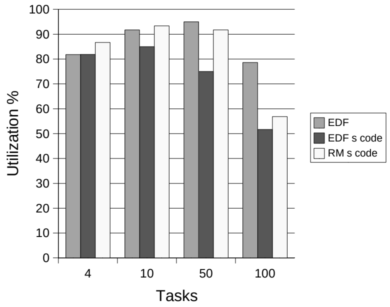

Figure 22: CPU utilization

Analyzing System Code. System code is amenable to program and schedulability analysis. There are at least two interesting problems that involve checking time safety: (1) is some given E code time-safe, i.e., do all tasks released by the E code complete on time, with respect to a given scheduling strategy and WCETs; and (2) does some given S code guarantee the time-safe execution of some given E code and does the S code follow a given scheduling strategy? For general E code with conditional branching, the first problem is difficult but becomes easier if the E code has a particular structure, e.g., is generated from Giotto or simply describes a set of periodic tasks [10]. In this case, the second problem can be solved fast even for non-trivial scheduling schemes such as non-preemptive scheduling [11]. Thus time safety of E code combined with S code can be verified by the microkernel at run-time, e.g., as part of the integrity check in the idle task. Another interesting problem is to improve time safety checking using control-sensitive program analysis techniques. Note that a control-insensitive check is a conservative approximation, which may fail on a time-safe program because the check considers program paths that are actually never taken.

Composing System Code. An important feature of system code is its composability. E code may be composed with other E code at compile time, or even at run-time through the trigger queue of the E machine. Logically, the reactive behavior of E code does not change when composed with other E code since E code execution is instantaneous.

However, operationally, the instantaneousness of E code execution degrades with the number of E code instructions executed at the same instant. S code may also be composed with other S code at compile time, or at run-time through the thread set. In general, composing E code that uses S code for task scheduling requires regenerating the S code from scratch unless the S code was generated according to a compositional scheduling strategy. For example, if S code components are assigned exclusive time slots in which tasks are dispatched, then the composed S code is time-sharing, i.e., dispatches at most a single task at the same time, provided each S code component is already time-sharing. Thus S code can be used to study and utilize compositional scheduling strategies. Note that the time-triggered architecture [15] already offers a similar compositional strategy to time-share a communication bus that connects a distributed and fault-tolerant system of computers.

Partial System Code. If the microkernel has a default task scheduler, then it is not necessary that system code describes all behaviors of a real-time program. In fact, the microkernel can generate missing system code at run-time. For example, S code may only dispatch a subset of all tasks. The task scheduler of the microkernel can then either dispatch the rest of the tasks whenever the S code execution completed, or else generate additional S code that dispatches the remaining tasks. Once the additional S code has been generated, it can execute repeatedly without the need for the task scheduler. Besides improved run-time performance, a benefit at design time is that prototypes of system code can be developed gradually and executed before the code is complete. We have already taken advantage of this feature in the development and testing of the microkernel and the Giotto compiler.

System code may also be optimized at run-time based on information only available at run-time. For example, in the spirit of dynamic code optimization at run-time [14], the microkernel can reduce the number of task preemptions by rearranging S code instructions. We have used this technique for our benchmarks to obtain non-preemptive S code from preemptive S code.

Portable and Mobile System Code. Portability and mobility of real-time programs are truly as challenging as they are desirable. Here are two examples: embedded systems such as control computers for satellites or power plants, which cannot easily be rebooted, would benefit from portable and mobile real-time code; or the performance of communication devices such as cell phones or network routers could be software-calibrated remotely while speaking or downloading. Predictability and composability of system code enable portability and mobility. For example, *environment-triggered* system code [9] whose triggers only refer to events such as the system clock tick or external signals is portable code as long as time safety can be guaranteed. It is also mobile code because system code is represented hardware-independently as byte code with symbolic references to functional code.

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Tasks	Mode	System code (μs)			U	P	S code	E code	EDF	E+S code	S code
(#)		peak	min	average	(%)	(#)	(μs)	(μs)	(μs)	(#)	(#)
4	EDF	12.207	1.356	3.778	0.818	4	0	4.653	1.473	30	0
	EDF sc	20.888	2.170	3.884	0.818	4	1.411	5.574	0	60	30
	EDF sco	infeasible								64	34
	RM sc	13.563	1.356	3.600	0.867	5	1.549	4.643	0	48	18
10	EDF	21.159	1.356	6.129	0.917	4	0	8.792	3.658	54	0
	EDF sc	26.855	2.170	4.472	0.850	4	1.565	9.510	0	107	53
	EDF sco	infeasible								111	57
	RM sc	17.632	1.356	4.386	0.934	5	1.762	8.842	0	108	54
50	EDF	129.120	1.356	21.767	0.950	4	0	44.972	18.508	174	0
	EDF sc	120.710	1.899	6.822	0.750	0	2.207	52.882	0	347	173
	EDF sco	115.020	1.899	6.843	0.750	0	2.212	52.885	0	351	177
	RM sc	100.910	1.356	7.263	0.917	5	3.036	48.450	0	468	294
100	EDF	287.000	1.356	38.573	0.786	4	0	81.749	36.074	318	0
	EDF sc	247.400	1.899	7.628	0.517	0	2.258	116.190	0	636	318
	EDF sco	248.210	2.170	7.643	0.518	0	2.248	116.790	0	640	322
	RM sc	177.950	1.356	8.625	0.569	2	3.897	98.331	0	912	594

Table 1: Tasks with long execution times

Tasks	Mode	System code (μs)			U	P	S code	E code	EDF	E+S code	S code
(#)		peak	min	average	(%)	(#)	(μs)	(μs)	(μs)	(#)	(#)
4	EDF	12.207	1.356	3.087	0.350	1	0	4.608	1.384	30	0
	EDF sc	20.888	2.170	4.065	0.350	1	1.428	5.513	0	60	30
	EDF sco	20.888	2.170	4.061	0.351	0	1.439	5.528	0	61	31
	RM sc	12.478	1.356	3.083	0.352	1	1.619	4.933	0	48	18
10	EDF	21.159	1.356	4.730	0.350	1	0	8.647	3.460	54	0
	EDF sc	27.127	2.170	4.676	0.350	1	1.595	9.588	0	108	54
	EDF sco	27.127	27.127	4.682	0.350	0	1.601	9.668	0	109	55
	RM sc	16.819	1.356	3.988	0.351	1	1.843	8.958	0	108	54
50	EDF	126.680	1.356	17.929	0.417	1	0	43.574	16.983	174	0
	EDF sc	113.390	1.899	6.799	0.334	0	2.152	52.417	0	348	174
	EDF sco	116.100	1.899	6.816	0.333	0	2.163	52.701	0	349	175
	RM sc	87.348	1.356	7.156	0.384	1	3.239	47.878	0	468	294
100	EDF	281.850	1.356	36.765	0.601	2	0	81.655	35.190	318	0
	EDF sc	247.120	1.899	7.584	0.368	0	2.229	113.880	0	636	318
	EDF sco	251.740	1.899	7.591	0.367	0	2.230	115.550	0	638	320
	RM sc	174.420	1.356	8.590	0.400	4	3.935	97.230	0	912	594

Table 2: Tasks with medium execution times

Tasks	Mode	System code (μs)			U	P	S code	E code	EDF	E+S code	S code
(#)		peak	min	average	(%)	(#)	(μs)	(μs)	(μs)	(#)	(#)
4	EDF	12.207	1.356	3.091	0.352	1	0	4.693	1.382	30	0
	EDF sc	20.888	2.170	4.063	0.350	1	1.435	5.468	0	60	30
	EDF sco	20.888	2.170	4.061	0.350	0	1.441	5.548	0	61	31
	RM sc	12.478	1.356	3.084	0.351	1	1.623	4.942	0	48	18
10	EDF	21.159	1.356	4.730	0.350	1	0	8.661	3.460	54	0
	EDF sc	27.127	2.170	4.677	0.351	1	1.595	9.606	0	108	54
	EDF sco	27.127	2.170	4.682	0.352	0	1.601	9.683	0	109	55
	RM sc	16.819	1.356	3.988	0.351	1	1.843	8.959	0	108	54
50	EDF	131.020	1.356	16.902	0.234	1	0	41.721	16.905	174	0
	EDF sc	116.370	1.899	6.742	0.200	0	2.160	51.498	0	348	174
	EDF sco	118.270	1.899	6.754	0.200	0	2.169	51.701	0	349	175
	RM sc	89.789	1.356	7.025	0.201	1	3.286	46.539	0	468	294
100	EDF	300.560	1.356	34.913	0.349	1	0	81.572	34.844	318	0
	EDF sc	242.510	1.899	7.580	0.200	0	2.216	115.570	0	636	318
	EDF sco	243.600	1.899	7.580	0.200	0	2.211	115.700	0	637	319
	RM sc	177.140	1.356	8.535	0.201	1	3.979	98.032	0	912	594

Table 3: Tasks with short execution times