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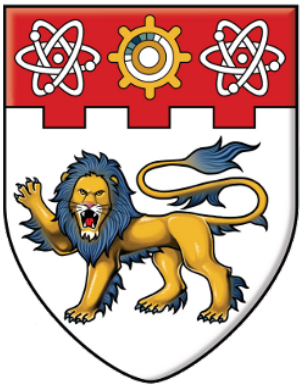

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Micrium μC/OS-III++

Submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Computer Engineering of the Nanyang Technological University

by

Do Nhat Minh

School of Computer Engineering

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Abstract

Real-time operating systems play an important role in time and safety-critical software systems used in many fields, such as avionics, automotives and defense applications. μC/OS-III is an open-source real-time operating system which aims to be used on embedded devices with restricted resources. μC/OS-III has many useful features; however, it does not have better algorithms proven in more recent advances in real-time systems research.

In this thesis, a hybrid scheduler where Earliest Deadline First scheduling runs on top of Fixed-Priority scheduling and Priority Ceiling Protocol for time-guaranteed resource sharing are implemented to enhance μC/OS-III.

Acknowledgements

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Chapter 1

Introduction

An operating system (OS) is a collection of software, or software components, which can be characterized as serving the following purposes, (1) interfacing with the underlying hardware to provide convenient abstractions for application programmers, and (2) managing the programs running on the system so that misbehaving programs do not impede others (Witchel, E. , 2009).

A real-time operating system is an OS which must adhere to a real-time constraint. In such a system, the timeliness of the results from programs are as important as the correctness of such solutions. The system risks catastrophic failures if deadlines are missed. Some important applications for real-time operating systems are in avionics and automotives, where missing task deadlines leads to lives lost.

μC/OS-III is an open-source priority-based preemptive real-time multitasking operating system for embedded systems. It has many useful features which aim to cut development time (Labrosse, J. J. , 2010, pp. 27-31).

However, μC/OS-III does not implement deadline management but defers this task to the programmer. Moreover, uC/OS-III has no facility to specify nor keep track of the deadlines for running tasks of the system.

1.1 Goal

The goal of this thesis is to implement better algorithms for μC/OS-III. For task scheduling, a hybrid scheduler where Earliest Deadline First scheduling runs on top of Fixed-Priority Scheduling is implemented. For resource sharing with mutexes, Priority Ceiling Protocol is implemented. In addition, a new type of tasks, namely recurrent tasks, is introduced as a complement to the new scheduler.

1.2 Overview

This thesis is divided into the following chapters.

Background explains concepts of scheduling algorithms and protocols for mutex acquisition and release.

Literature Review summarizes how Earliest Deadline First and Priority Ceiling Protocol is implemented for Ada 2005.

Overview of μC/OS-III provides a brief introduction to the current state of μC/OS-III regarding the scheduler and mutex operations.

Enhancements to μC/OS-III discusses how several enhancements to μC/OS-III are implemented.

Experiment introduces a sample application developed to test the new capabilities of μC/OS-III.

Results shows benchmarks for the new code, as well as evaluation for these benchmarks.

Conclusion summarizes the thesis and discusses future directions.

Chapter 2

Background

2.1 Scheduling Algorithms

A scheduling algorithm is an algorithm to determine the ordering of task executions in order to maximize resource utilization, while satisfying safety and correctness (Liu, C. L. and Layland, J. W. , 1973).

A real-time system consists of a number of tasks, each of which has a deadline and a period. Tasks must be completed before their deadlines or risk catastrophic consequences, e.g. a plane might crash if the task that sends sensor failure status misses deadlines. Task period is the interval between release times of instances of a task. Request rate is the reciprocal of task period. A task set is a collection of tasks to be scheduled. A task set is feasible when there exists an ordering where no deadline is missed.

2.1.1 Rate Monotonic Scheduling

Rate Monotonic Scheduling (RMS) belongs to the class of fixed priority scheduling algorithms. A fixed priority scheduling algorithm is a scheduling algorithm where task orderings are based on statically assigned priorities of the tasks. The rate monotonic priority assignment assumes that a task with higher request rate is assigned a higher priority. Liu, C. L. and Layland, J. W. (1973) have proven that for fixed priority scheduling, if there exists a feasible assignment, the rate

monotonic assignment is also feasible. In other words, RMS is optimal.

2.1.2 Utilization Analysis

CPU utilization for a task is the ratio between the time spent in execution and its period. CPU utilization for a task set is the summation of CPU utilization of each task in the set.

$$U = \sum_{i=1}^{n} \frac{C_i}{T_i}$$

where C_i is execution time and T_i is period for task i, n is the number of tasks in the task set and U is CPU utilization.

2.1.3 Utilization Analysis for RMS

It is proven that CPU utilization for a task set in RMS must be kept below an upper bound in order to guarantee feasibility. This upper bound is

$$U_{RMS} \leq n(2^{\frac{1}{n}} - 1)$$

where n is the number of tasks in that task set and U_{RMS} is CPU utilization (Liu, C. L. and Layland, J. W. , 1973).

As n tends towards infinity, this expression will tend towards

$$\lim_{n \to \infty} n(2^{\frac{1}{n}} - 1) = \ln 2 \approx 0.693147$$

As a rule of thumb, a task set is feasible under fixed priority scheduling when its CPU utilization is below 69.3%. The other 30.7% of CPU time can be reserved for other non real-time tasks.

However, this upper bound is pessimistic. It has been shown that a randomly generated task set will meet all deadlines when utilization is below 85% if exact task deadlines and periods are known, which might be difficult to achieve (Lehoczky, J.; Sha, L. and Ding, Y. , 1989).

2.1.4 Earliest Deadline First Scheduling

Earliest Deadline First Scheduling (EDF) is a scheduling algorithm where task orderings are based on deadlines of task instances. Under this scheme, an instance

of a task is assigned highest priority if its deadline is nearest, while an instance of a task with a deadline that is farthest is assigned the lowest priority.

2.1.5 Utilization Analysis for EDF

The utilization bound for EDF is

$$U_{EDF} \leq 1$$

where U_{EDF} is the CPU utilization (Liu, C. L. and Layland, J. W. , 1973).

From the utilization bounds for RMS and EDF, it is trivial to see that EDF guarantees all deadlines of a task set at a higher load than RMS. Therefore, EDF is more desirable from a resource utilization standpoint.

2.2 Resource Sharing with Mutual Exclusion

In order to maximize utility of resources in computer systems, resources are shared among the tasks that need them. These resources include hardware such as printers or software such as a region of computer memory. However, some resources must only be accessed by one task at a time. Examples include printers where unprotected, concurrent access to the print queue will result in sentences from different documents interleaving each other.

Mutual exclusion, or mutex, is a technique to protect such resources from concurrent access. Mutex was first identified and an implementation for which was first introduced by Dijkstra in his seminal paper (Dijkstra, E. W. , 1965).

2.2.1 Priority Inversion

In the context of real-time systems, there is a problem of priority inversion in the use of mutexes for resource sharing. Priority inversion occurs when a high priority task wants to access a shared resource and is blocked by a lower priority task holding the mutex for that resource.

Figure 2.1 shows an example of priority inversion. In this example, P_1 has highest priority, while P_3's priority is the lowest. At t_0, P_3 begins execution. At

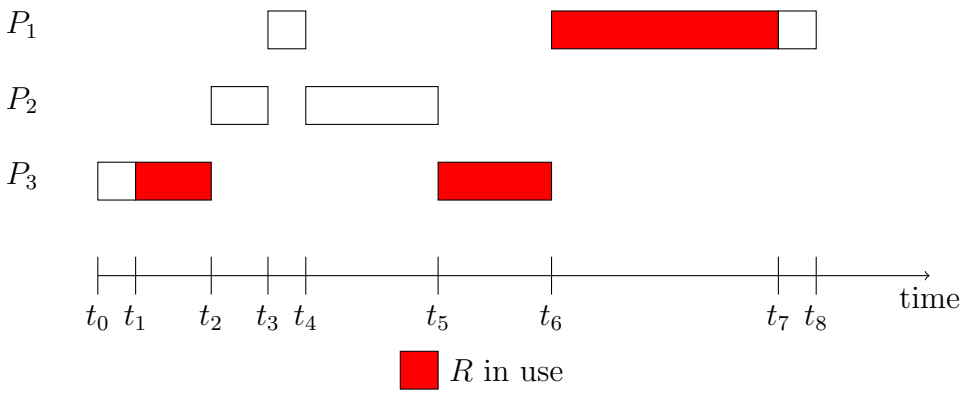

Figure 2.1: Priority Inversion

t_1, P_3 accquires the mutex R. At t_2, P_3 is preempted by P_2. At t_3, P_1 preempts P_2 and then at t_4 tries to acquire R, but is blocked P_3. P_2 then resumes execution. P_2 finishes execution at t_5. P_3 then resumes execution and releases R and finishes execution at t_6. P_1 then resumes execution, having successfully acquired mutex for R. At t_7, P_1 releases R and finishes execution at t_8.

In the above example, the highest priority task, namely P_1, is preempted by a lower priority task, namely P_2. It is easy to see that this example can be expanded to include multiple medium priority tasks, where the highest priority task is preempted consecutively by those tasks. In that case, the highest priority task may even miss its deadline because of the chain blocking of those lower priority tasks.

A real-life example of priority inversion is the incident of Mars Pathfinder spacecraft. There were many software tasks running on the Mars Pathfinder's VxWorks real-time operating system. The high priority task `bc_dist` was blocked by the much lower priority task `ASI/MET`, which in turn was blocked by other medium priority tasks. `bc_dist` therefore missed its deadline, which was before the execution of the `bc_sched` task. The software on Mars Pathfinder dealt with this missed deadline by rebooting itself. Although no catastrophe resulted, the rest of the activities for that day was only accomplished the next day (Reeves, G. E. , 1997).

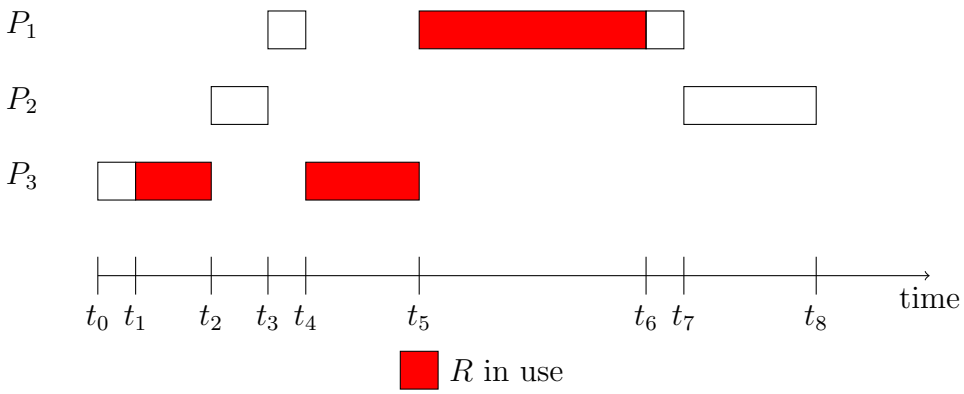

Figure 2.2: Priority Inheritance Protocol

2.2.2 Priority Inheritance Protocol

In order to solve the problem of Priority Inversion, Lui S. et. al. proposed a class of Priority Inheritance Protocols in their seminal 1990 paper (Lui, S.; Rajkumar, R. and Lehoczky, J.P. , 1990). The basic idea for Priority Inheritance Protocols is when a lower priority task blocks a higher priority task inside its critical section, it is promoted to the same priority as that higher priority for the duration of its critical section.

Figure 2.2 shows how priority inheritance can help mitigate the problem of priority inversion. The task set illustrated is the same as in figure 2.1. The tasks are scheduled the same way as in figure 2.1 from t_0 to t_4. However, when P_1 tries to take the mutex R and is blocked by P_3, P_3's priority is raised to be the same as P_1's. Thus, P_2 is no longer able to preempt P_3 and P_3 can run until it releases R and finishes at t_5. As P_1's priority is higher than P_2's, it is scheduled to run at t_5. P_1 releases R at t_6 and finishes at t_7, as which point P_2 is scheduled to run till finish.

2.2.3 Deadlock

In the use of mutexes for resource sharing, a deadlock occurs when a task waits on a mutex to a resource held by another task, which in turn is waiting for another mutex held by the first task, as illustrated in figure 2.3.

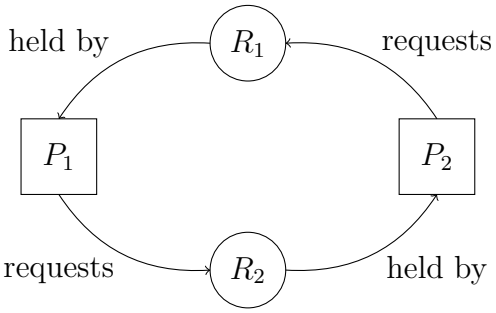

Figure 2.3: Deadlock - Resource Allocation Graph

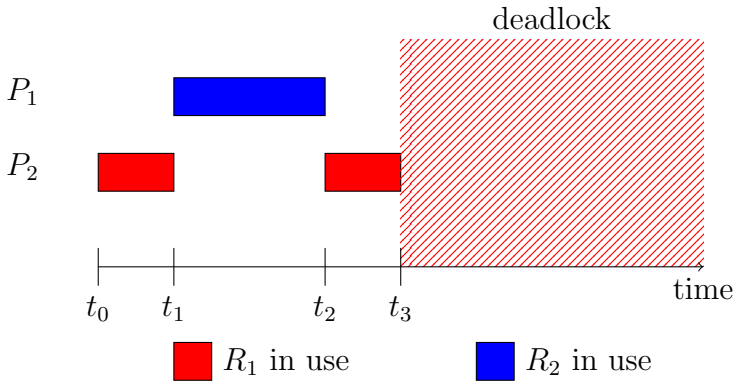

Figure 2.4: Deadlock

Although Priority Inheritance Protocol is well-suited to handle the problem of priority inversion, it does not help to prevent deadlocks, as illustrated in figure 2.4. In this example, P_1 has higher priority than P_2. At t_0, P_2 starts executing and acquires the mutex R_1. At t_1, P_1 becomes ready and starts executing immediately, as it has higher priority than P_2. P_1 acquires the mutex R_2 at the start of its execution. At t_2, P_1 tries to take R_1 but is blocked by P_2, which holds that mutex. With P_1 blocked, P_2 then resumes execution and at t_3 tries to take R_2, which is currently held by P_1. As P_1 and P_2 are now waiting for each other, no progress can be made and a deadlock occurs.

Necessary Conditions for Deadlocks

Necessary conditions for deadlocks to arise, also known as the Coffman conditions, are as follows. If in a system, any one of the four conditions is not met, deadlocks

will not occur (Coffman, E. G. Jr.; Elphick, M. and Shoshani, A. , 1971):

Mutual Exclusion

At most one task can have access to a resource at any instant.

Hold and Wait

After gaining access to the resource, the task has to wait before it can proceed; e.g. it has to wait for other resources to become available.

No Preemption

The OS cannot take away a resource from the task once it has successfully gained access to the resource.

Circular Wait

There exists a set of resources $P = \{P_1, P_2, \ldots, P_n\}$ where P_1 is waiting for a resource held by P_2, which is waiting for a resource held by P_3, $\ldots$, and so on, with P_n waiting for a resource held by P_1.

Deadlock Handling

There exist approaches to handling deadlocks, namely deadlock detection, deadlock prevention and deadlock avoidance.

Under deadlock detection, deadlocks are allowed to happen. On the other hand, the OS reserves the right to kill and restart tasks involved in the deadlock and the acquired resources are preempted to give to other tasks in an attempt to break the deadlock. However, restarting tasks and preempting resources could lead to inconsistent state for the resource under protection.

Deadlock prevention is implemented by breaking one of the necessary conditions for deadlocks to occur. Breaking mutual exclusion is imposible for resources which must be accessed by only one task. Resource holding or hold and wait can be prevented by making all tasks acquiring all resources before they can proceed; however, this is a very inefficient use of resources. Resource preemption is infeasible for certain resources. Finally, circular wait can be prevented by giving specific ordering for all resources and requiring all tasks to adhere to this ordering for resource acquisition.

Under deadlock avoidance, the system is prevented from ever reaching an unsafe state. This requires the OS to have some information about resource usage of each task. One algorithm for deadlock avoidance is Priority Ceiling Protocol, which is introduced in the next section.

2.2.4 Priority Ceiling Protocol

Priority Ceiling Protocol (PCP) extends Priority Inheritance Protocol by adding more restrictions on mutex acquisition so as to implement deadlock avoidance. Under this scheme, each mutex is assigned a priority ceiling which is the same priority as the highest priority task that will use that mutex. A task is allowed to acquire a mutex when its priority is higher than the system ceiling, which is equal to the highest ceiling among the ceilings of mutexes currently locked by tasks other than the current task. When a low priority task blocks higher priority tasks from acquiring a mutex, the priority of the low priority task is raised to the highest priority among the higher priority tasks, so in this regard, it is the same as Priority Inheritance Protocol (Lui, S.; Rajkumar, R. and Lehoczky, J.P. , 1990).

Figure 2.5 shows how PCP can handle deadlocks and still prevent chained blocking like Priority Inheritance Protocol. In this example, P_1 has the highest priority, followed by P_2 and then P_3. Mutexes R_1 and R_2 are both used by P_1 and P_2 and thus, under PCP, are assigned priority ceilings which are at the same priority as P_1's. At t_0, P_3 begins execution and acquires mutex R_1. The system ceiling is raised to be the priority ceiling of R_1, which is the same as P_1's priority. At t_1, P_2 starts executing, as it has higher priority than P_3. At t_2, P_1 preempts P_2 and begins execution. At t_3, P_1 tries to acquire R_2, but is denied and put into pending state, as its priority is not higher than the current system ceiling. P_3 inherits P_1's priority for blocking P_1 and is scheduled to run immediately. It then acquires successfully R_2 at t_4, as there is no other active mutex acquired by any task other than P_3, and runs till completion at t_5, at which point it releases both R_1 and R_2. P_1 is then woken up, acquires R_2, runs until t_6 and acquires successfully R_1. P_1 completes its run at t_7, at which point it releases both R_1 and

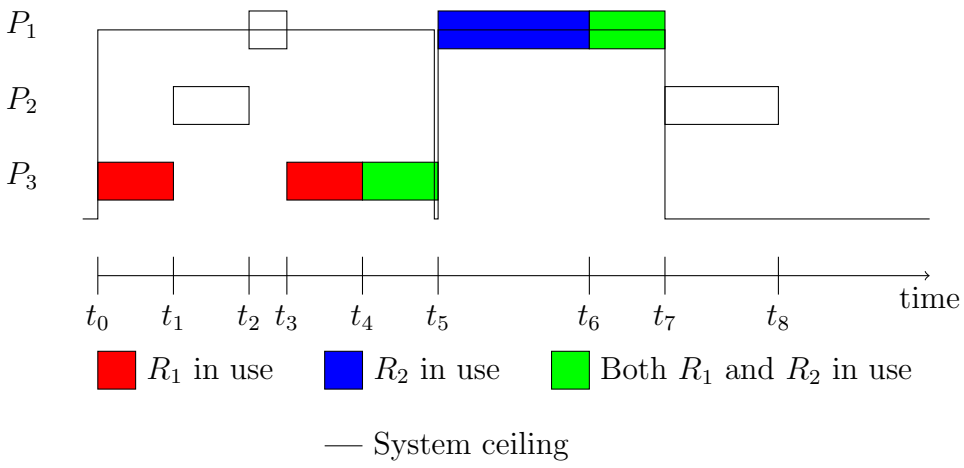

Figure 2.5: Priority Ceiling Protocol

R_2. The system ceiling is reset to be below P_3's priority. P_2 is then scheduled to run till completion at t_8.

Chapter 3

Literature Review

Burns, A.; Wellings, A. J. and Zhang, F. (2009) proposed implementing Earliest Deadline First Scheduling on top of Fixed Priority Scheduling, also known as Rate Monotonic Scheduling, as the hybrid scheduling algorithm for Ada 2005. The system model is that a small number of tasks at a low priority are scheduled with EDF, while other higher priority tasks are scheduled with RMS. In this system, the user can specify which priority levels are scheduled with EDF and which higher priority levels are scheduled with RMS.

Cheng, A. M. K. and Ras, J. (2007) proposed an implementation of Priority Ceiling Protocol for Ada 2005. The ceiling priorities of the mutexes are saved into an array, while the locking statuses of them are saved into another. Upon successful locking of a mutex, the task identifier and original priority of the task is saved into an array private to the scheduler. If a task requests for a lock on a mutex but is unsuccessful, it will be queued for future attempt, while the task holding the mutex will be raised in priority to be the same as that task if applicable. On release of a mutex, if there are other tasks waiting on that mutex, the task with highest priority will be woken up and take control of the mutex while the original owner of the mutex will be reset to the original priority.

Chapter 4

Overview of Micrium μC/OS-III

Micrium μC/OS-III is a preemptive multitasking real-time OS targeting embedded devices. In this chapter, the inner working of this OS is examined.

4.1 Task Model

Tasks in μC/OS-III are implemented as normal C functions with their own accompanying stacks and Task Control Blocks. However, unlike normal C functions, tasks are not allowed to return (Labrosse, J. J. , 2010, p. 83).

4.1.1 Types of Tasks

There are two types of tasks, namely run-to-completion and infinite loop.

Run-to-completion tasks must call `OSTaskDel()` at the end of the function (Labrosse, J. J. , 2010, p. 84).

Listing 4.1: Run-to-completion Task

```
void RunToCompletionTask(void* p_arg) {
    OS_ERR err;

    /* do work */

    /* a NULL pointer indicates the current task
     * should be deleted
     */
```

```
    OSTaskDel((OS_TCB*) 0, &err);
}
```

Infinite-loop tasks do not need to call `OSTaskDel()`; however, they must make calls to services in the OS inside the infinite loop in order to yield control of the CPU to other tasks (Labrosse, J. J. , 2010, p. 85).

Listing 4.2: Infinite-loop Task

```
void RunToCompletionTask(void* p_arg) {
    OS_ERR err;

    /* initialization */
    while (1) {             /* or for(;;) */
        /* do work */
        /* must call one of the following
         *     OSFlagPend()
         *     OSMutexPend()
         *     OSPendMulti()
         *     OSQPend()
         *     OSSemPend()
         *     OSTimeDly()
         *     OSTimeDlyHMSM()
         *     OSTaskQPend()
         *     OSTaskSemPend()
         *     OSTaskSuspend()
         *     OSTaskDel()
         */
    }
}
```

4.1.2 Task Creation

In order to create a new task, the user must provide an allocated Task Control Block (`OS_TCB`) and other arguments to `OSTaskCreate()`.

Listing 4.3: `OSTaskCreate()`

```
void OSTaskCreate (OS_TCB        *p_tcb,
                   OS_CHAR       *p_char,
                   OS_TASK_PTR    p_task,
                   void          *p_arg,
```

```
                    OS_PRIO          prio,
                    CPU_STK         *p_stk_base,
                    CPU_STK_SIZE     stk_limit,
                    CPU_STK_SIZE     stk_size,
                    OS_MSG_QTY       q_size,
                    OS_TICK          time_slice,
                    void            *p_ext,
                    OS_OPT           opt,
                    OS_ERR          *p_err);
```

Task Control Block (`OS_TCB`) is a C `struct` containing necessary task-related information on which the whole of μC/OS-III depends for proper functioning. The information contained in a TCB includes a pointer to the top of stack, a pointer to the C function underlying this task, the current state of this task, the priority of this task and many more.

The bare mininum arguments which the user must provide to create a task are a task control block (`OS_TCB*`), a C function implementing that task (`OS_TASK_PTR` which is a `typedef` of `void (*)(void*)`), a positive integer as priority (`OS_PRIO`), an allocated array as the task stack (`CPU_STK*`) and an `OS_ERR*` for error reporting.

4.2 Scheduling Algorithm

μC/OS-III has a priority-based, preemptive scheduler implementing Fixed-Priority Scheduling (Labrosse, J. J. , 2010, p. 141).

Priority-based

Each task are assigned a static priority. The OS schedules them based on their priorities.

Preemptive

Higher priority tasks can preempt lower priority tasks, which means that during execution of a low priority task, if a high priority task is ready, the low priority task may be suspended so as to give CPU time to the high priority task.

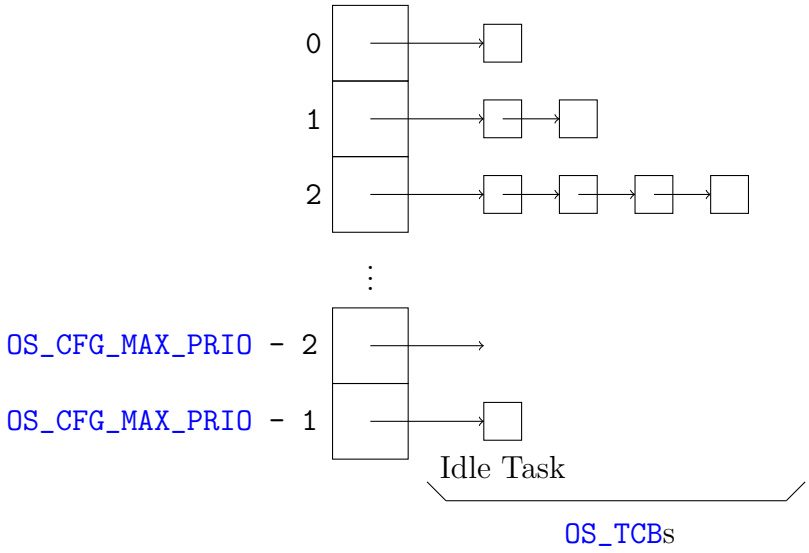

Figure 4.1: Ready List

In order to schedule the tasks, the OS keeps track of ready tasks in ready lists. Tasks with the same priority are put in the same ready list. `OSRdyList` is an array of singly linked lists, where each node is an `OS_TCB`, as shown in figure 4.1.

When a task yields the CPU, the scheduler finds a non-empty linked list with highest priority in `OSRdyList`, removes the first `OS_TCB` from the list and context switches to the task described by that TCB.

4.3 Resource Sharing with Mutexes

μC/OS-III implements Priority Inheritance Protocol for mutexes. There are three basic operations on a mutex, namely mutex creation, acquisition and release. μC/OS-III allows a task to acquire a mutex multiple times (also known as nesting); however, that task must release the mutex an equal number of times.

4.3.1 Mutex Creation

In order to create a mutex, the user must call `OSMutexCreate()` passing in an allocated `OS_MUTEX*`, an optional `OS_CHAR*` as the name of the mutex, and an allocated `OS_ERR*` for error reporting.

Listing 4.4: `OSMutexCreate()`

```
void OSMutexCreate(OS_MUTEX *p_mutex,
                   OS_CHAR  *p_char,
                   OS_ERR   *p_err);
```

4.3.2 Mutex Acquisition

In order to acquire a mutex, the user must call `OSMutexPend()` passing in a created `OS_MUTEX*`, an optional `OS_TICK` as timeout (`0` for no timeout), an `OS_OPT` which are options or'd together, an optional `OS_TS*` to save the timestamp when the mutex is released with `OSMutexPost()`, and an `OS_ERR*` for error reporting. Below is the signature of the function, along with the pseudocode explaining how it works.

Listing 4.5: `OSMutexPend()`

```
void OSMutexPend(OS_MUTEX *p_mutex,
                 OS_TICK   timeout,
                 OS_OPT    opt,
                 OS_TS    *p_ts,
                 OS_ERR   *p_err)
{
    check if the arguments passed in are valid;
    if the mutex does not have an owner {
        set nesting level to 1;
        assign the current task as the owner;
        return;
    }

    if the owner of the mutex is the current task {
        increase the nesting level;
        return;
    }

    /* here we know that the mutex already has an
     * owner, which is not the current task.
     *
     *
     * the next if statement implements Priority
     * Inheritance Protocol
```

```
     */
    if the current task has a higher priority
        than the owner {
        change the active priority of the owner
            to be the same as the current task;
    }

    block current task and give control back
        to the OS;

    /* the task resumes here when the OS has given
     * the current mutex to it; i.e. acquisition is
     * successful.
     */
    return success;
}
```

4.3.3 Mutex Release

In order to release a mutex, the user must call `OSMutexPost()` passing in a created `OS_MUTEX*`, an `OS_OPT` for options, and an `OS_ERR*` for error reporting. Below is the signature of the function, along with pseudocode explaining how it works.

Listing 4.6: `OSMutexPost()`

```
void OSMutexPost(OS_MUTEX *p_mutex,
                 OS_OPT    opt,
                 OS_ERR   *p_err)
{
    check if the arguments passed in are valid;
    if the current task is not the owner {
        return failure;
    }

    decrease the nesting level on mutex;
    if the nesting level is not zero {
        return failure;
    }

    /* here we know that the current task has
     * released the mutex thoroughly with no more
     * nesting.
     */
```

```
    if there are no more tasks waiting on this mutex
       {
        return success;
    }

    adjust the priority of the current task back to
        its original level;
    give ownership of this mutex to the task waiting
        with highest priority;

    return success;
}
```

Chapter 5

Enhancements to μC/OS-III

In this chapter, several enhancements to μC/OS-III are discussed. A new kind of tasks is introduced, namely recurrent tasks. In addition, Earliest Deadline First is implemented as a new scheduler for μC/OS-III, while Priority Ceiling Protocol is implemented for mutex operations.

5.1 Earliest Deadline First Scheduling

Earliest Deadline First scheduling is a dynamic priority scheduling scheme. The priority of a task in EDF does not depends only on a static priority assigned at creation, but depends on its runtime deadline.

A new field is added to the `struct OS_TCB`, namely `AbsDeadline` of type `OS_TICK`, to represent the absolute deadline in milliseconds since the start of μC/OS-III. By default, this field is set to be the maximum value `OS_TICK` can take, which is $2^{64} - 1$ milliseconds $\approx 5.84942 \times 10^6$ centuries, guaranteeing that deployed devices running this modified μC/OS-III reach their end-of-life long before this timestamp is reached.

When inserting tasks into the ready list, the tasks are sorted in ascending order of absolute deadlines at each priority level. The implementation for selecting the next task to run from the ready list is still the same as the μC/OS-III's previous implementation.

5.2 Recurrent Tasks

A recurrent task is a run-to-completion task which is created repeatedly at regular intervals. The interval between two instances of a recurrent task is its period. Introduction of this type of tasks complements Earliest Deadline First.

In order to implement this kind of tasks, the OS must keep track of the period as well as the relative deadline of each task. A new type is introduced to keep tract of these information, namely `OS_TD`, short for *task descriptor*.

Listing 5.1: `OS_TD`

```
typedef struct os_td OS_TD;

struct os_td {
    OS_TD       *PrevPtr;
    OS_TD       *NextPtr;
    OS_TICK      Period;
    OS_TICK      RelDeadline;
    OS_TICK      AbsSpawnTime;
    CPU_CHAR    *NamePtr;
    OS_TASK_PTR  TaskEntryAddr;
    void        *TaskEntryArg;
};
```

In order to create a recurrent task, the user must call `OSRecTaskCreate()`, the signature of which is provided below. The minimal required arguments which the user must provide are an allocated `OS_TD*`, the relative deadline of the task (`OS_TICK`), the period of the task (`OS_TICK`), the C function implementing the task (`OS_TASK_PTR`) and an allocated `OS_ERR*` for error reporting.

Listing 5.2: `OSRecTaskCreate()`

```
void OSRecTaskCreate (OS_TD          *p_td,
                      OS_TICK         rel_deadline,
                      OS_TICK         period,
                      OS_TICK         delay,
                      CPU_CHAR        *p_name,
                      OS_TASK_PTR     p_task,
                      void            *p_arg,
                      OS_ERR          *p_err);
```

Below is a skeleton for a C function implementing a recurrent task. The OS will call `OSTaskDel()` after each instance of the recurrent task has finished on behalf of the user.

Listing 5.3: Recurrent Task

```
void RecurrentTask (void* p_arg)
{
    OS_ERR err;

    /* initialization */

    /* do work */

    /* there is no need to call any services by the
     * OS like in the case of infinite-loop task, or
     * call OSTaskDel() at the end like in the case
     * of run-to-completion task
     */
}
```

Each `OS_TD` is a node for a doubly linked list, named `OSTaskList`, maintained by the OS to be in ascending order of absolute spawn time.

A dedicated task, named `OSTaskSpawner`, is created at OS initialization time to create tasks from these task descriptors. Below is the pseudocode explaining how this task is implemented. As μC/OS-III requires a task to have a task control block (`OS_TCB`) and a stack, the new addition to the code asks the user to provide the number of tasks dynamically created at runtime on behalf of the user via a `#define`. At compilation time, a chunk of memory with size equal to the maximum number of `OS_TCB`, each accompanied with its own stack, is reserved. At runtime, `OSTaskSpawner` takes from that chunk of memory to create the required `OS_TCB` and stack for each recurrent task.

Listing 5.4: `OS_TaskSpawnerTask`

```
void OS_TaskSpawnerTask (void *p_arg)
{
    loop forever {
        if there is no task descriptor in
```

```
                the task list
            {
                sleep for 10 milliseconds;

                /* this task can be woken up mid-sleep if
                 * a task descriptor is added to the task
                 * list
                 */
            } else {
                sleep until the absolute spawn time
                    of the first task descriptor in
                    the task list;

                extract the first task descriptor in
                    the task list;

                create a task from that task descriptor;

                update the absolute spawn time of that
                    task descriptor to be the next
                    spawn time;

                reinsert that task descriptor into
                    the task list;
            }
        }
}
```

5.3 Priority Ceiling Protocol

The three operations on mutexes, namely mutex creation, acquisition and release, are modified to implement Priority Ceiling Protocol.

5.3.1 Mutex Creation

In addition to providing an allocated mutex (`OS_MUTEX*`), an optional name (`CPU_CHAR*`) and an `OS_ERR*` for error reporting, the user needs to provide the priority ceiling (`OS_PRIO`) and the relative deadline ceiling (`OS_TICK`) in order to create a mutex. The additional static ceiling information is required to implement Priority Ceiling Protocol.

Listing 5.5: `OSMutexCreate()` for Priority Ceiling Protocol

```
void  OSMutexCreate (OS_MUTEX *p_mutex,
                     OS_PRIO   prio_ceiling,
                     OS_TICK   rel_deadline_ceiling,
                     CPU_CHAR *p_name,
                     OS_ERR   *p_err);
```

All created mutexes are put into a singly linked list maintained by the OS.

5.3.2 Mutex Acquisition

A ceiling is defined as a pair of priority and relative deadline. The following helper function implements how two ceilings are compared, where a return value of `1` means the first ceiling is higher than the second ceiling, `0` means they are equal, while `-1` means the first is lower than the second ceiling.

Listing 5.6: `OSCompareCeilings()`

```
CPU_INT32S OSCompareCeilings (
    OS_PRIO first_prio,
    OS_TICK first_rel_deadline,
    OS_PRIO second_prio,
    OS_TICK second_rel_deadline)
{
    if (first_prio < second_prio ||
        (first_prio == second_prio &&
         first_rel_deadline < second_rel_deadline)) {
        return 1;
    }

    if (first_prio == second_prio &&
       first_rel_deadline == second_rel_deadline) {
        return 0;
    }

    return -1;
}
```

The arguments required are unchanged for `OSMutexPend()`. Below is the pseudocode describing how the new implementation works.

Listing 5.7: `OSMutexPend()` for Priority Ceiling Protocol

```
void OSMutexPend (OS_MUTEX *p_mutex,
                  OS_TICK   timeout,
                  OS_OPT    opt,
                  CPU_TS   *p_ts,
                  OS_ERR   *p_err)
{
    check if provided arguments are valid;
    if the ceiling of the current task is higher than
        the ceiling of the mutex {
        return failure;
    }

    /* the next two statements are where Priority
     * Inheritance Protocol and Priority Ceiling
     * Protocol differs
     */
    calculate the system ceiling of the current task;
    if the current mutex does not have an owner and
        the ceiling of the current task is higher
        than the system ceiling {
        set the nesting level of the current mutex
            to 1;
        make the current task the owner of the mutex;
        return success;
    }

    if the current task is already the owner of
        the current mutex {
        increase the nesting level of the
            current mutex;
        return success;
    }

    /* here the current task is not the owner of the
     * mutex and its request to acquire the mutex
     * cannot be satisfied
     *
     * the next if statement implements Priority
     * Inheritance Protocol
     */

    if the mutex already has an owner and
        its owner has lower priority or
        has the same priority but further
```

```
        absolute deadline than the current task {
        adjust the priority level and absolute
            deadline of the owner to be the same as
            the current task;
    }

    block the current task and give control back
        to the OS;

    /* the task resumes here when the OS has given
     * the current mutex to it; i.e. acquisition is
     * successful.
     */

    return success;
}
```

5.3.3 Mutex Release

Below is the pseudocode explaining how the new implementation works.

Listing 5.8: `OSMutexPost()` for Priority Ceiling Protocol

```
void  OSMutexPost (OS_MUTEX  *p_mutex,
                   OS_OPT     opt,
                   OS_ERR    *p_err)
{
    check if provided arguments are valid;
    if the current task is not the owner {
        return failure;
    }

    decrease the nesting level of the current mutex;
    if the nesting level is not zero {
        return failure;
    }

    /* here we know that the current task has
     * released the mutex thoroughly with no more
     * nesting
     */

    adjust the priority and absolute deadline of the
       current task back to their original values;
```

```
    if there are no more tasks waiting on this mutex
       {
        /* this is where Priority Inheritance
         * Protocol and Priority Ceiling Protocol
         * differs
         */
        find the mutex which has the task with
            highest priority and nearest deadline
            still waiting on that mutex;
        if that mutex does not have an owner {
            give ownership of that mutex to
                that task;
            make that task ready to run;
        }

        return success;
    }

    give ownership of this mutex to the task waiting
       with the highest priority;

    return success;
}
```

Chapter 6

Experiment

This chapter introduces an application to test the capabilities of the modified OS. The application, along with the enhanced μC/OS-III, is deployed to Texas Instruments's EvalBot (Texas Instruments , 2011). The application consists of three recurrent tasks, shown in the following table.

Task	**Period** (seconds)	**Relative Deadline** (seconds)	**Workload** (seconds)
P_1	3	3	1
P_2	5	5	1
P_3	7	7	3

Table 6.1: Task Listing

From the above table, it can be deduced that only one instance of each task is running at any time instance.

Each task makes use of two mutexes R_1 and R_2. The first instances of the three tasks are released at time 0. Below are pseudo code implementations of the three tasks, assuming mutex acquisition, mutex release and manipulating the robot takes negligible amount of time.

Listing 6.1: Task One (P_1)

```
void AppTaskOne (void* p_arg)
```

```
{
    acquire mutex R2;
    do work for one second;
    acquire mutex R1;
    turn the bot ninety degrees;
    release mutex R1;
    print "TASK ONE" to LCD;
    release mutex R2;
}
```

Listing 6.2: Task Two (P_2)

```
void AppTaskTwo (void* p_arg)
{
    acquire mutex R2;
    acquire mutex R1;
    do work for one second;
    print "TASK TWO" to LCD;
    release mutex R1;
    release mutex R2;
    write to SD Card;
}
```

Listing 6.3: Task Three (P_3)

```
void AppTaskThree (void* p_arg)
{
    acquire mutex R1;
    turn off all LEDs;
    toggle all LEDs;
    do work for one seconds;
    toggle all LEDs;
    do work for one seconds;
    toggle all LEDs;
    do work for one seconds;
    acquire mutex R2;
    print "TASK THREE" to LCD;
    release mutex R2;
    turn off all LEDs;
    release mutex R1;
}
```

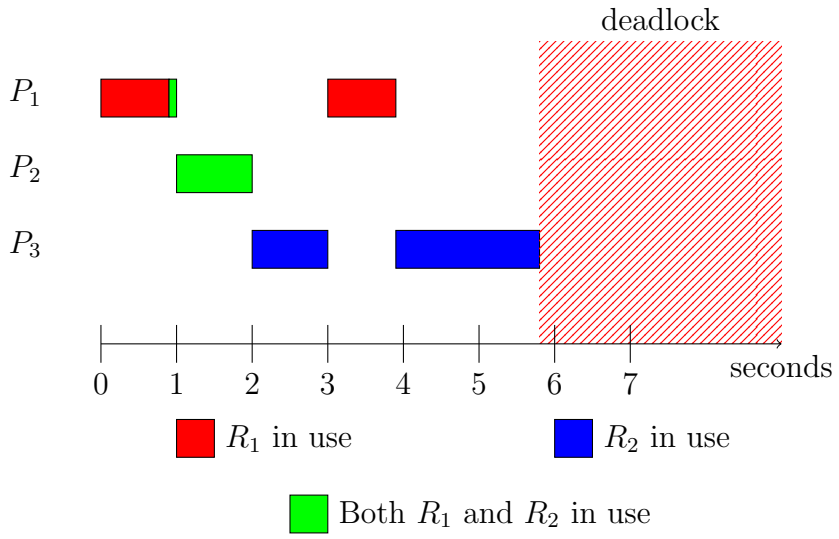

Figure 6.1: Task Run in Original μC/OS-III

6.1 Task Run in Original μC/OS-III

In the original version of μC/OS-III, the priority of each instance of each task is manually set such that P_1's priority is higher than P_2's and P_2's priority is higher than P_3's.

Firgure 6.1 shows that the system deadlocks early in its execution. At time 0, the first instances of all three tasks are released; however, only task P_1 starts executing, as it has the highest priority. P_1 executes until it finishes at time 1. After the first instance of P_1 finishes, the first instance of P_2 starts executing until it finishes at time 2. The first instance of P_3 starts executing right afterwards by acquiring R_2. At time 3, the second instance of P_1 is released and starts executing immediately, acquiring R_1. However, near the end of P_1's execution, when it tries to acquire R_2, it is blocked by P_3. As the original μC/OS-III implements Priority Inheritance Protocol, P_3 inherits P_1 priority and continues execution. At time 5, the second instance of P_2 is released but not scheduled to run as its priority is now below P_3's effective priority. P_3 continues execution until it tries to acquire R_1 and is blocked by P_1. At this point, both P_1 and P_3 blocks each other and P_2 waits for P_1's release of R_2, so no progress can be made and the system deadlocks.

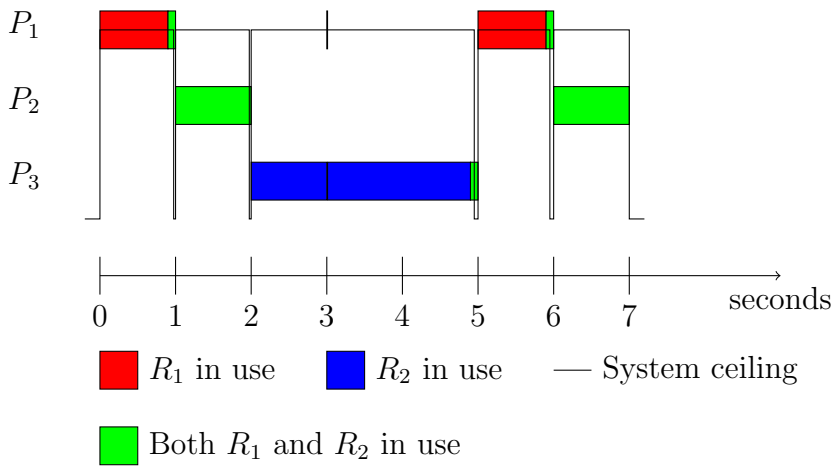

Figure 6.2: Task Run in μC/OS-III with Enhancements

In addition, the CPU utilization for this task set is as follows

$$\frac{1}{3} + \frac{1}{5} + \frac{3}{7} \approx 0.961904 > 0.693147$$

Therefore, this task set does not pass the schedulability test for Fixed-Priority Scheduling, which means that the system might miss deadlines during execution.

6.2 Task Run in μC/OS-III with Enhancements

In the enhanced version of μC/OS-III, all three tasks are assigned the same priority; therefore, each instance of a task has its priority assigned based on its runtime absolute deadline, i.e. they are scheduled with EDF.

Figure 6.2 shows how Priority Ceiling Protocol helps eliminate the deadline seen during the first seven seconds of runtime. In the first 3 seconds, the tasks run in the same way as in figure 6.1. However, at time 3, when the second instance of task P_1 is released and tries to acquire R_1, it is blocked as its priority does not exceed the current system ceiling. P_3 then inherits P_1's priority and continues execution. At time 5, the second instance of P_2 is released but not scheduled to run, as P_3's effective priority is higher than P_2's. P_3 finishes its execution at time 5, at which point in time the second instance of P_1 is scheduled to run. The deadlock no longer occurs.

In addition, this task set passes the schedulability test for Earliest Deadline First scheduling.

Chapter 7

Results

In this chapter, the enhanced μC/OS-III is benchmarked and the result of the benchmarks are evaluated. All benchmarks are run on TI's EvalBot.

7.1 Benchmarking Tool

`OS_TS_GET()` is used for getting timestamps in order to perform benchmarks. On TI's EvalBot, this function reads from the `DWT_CYCCNT` register, which is a 32-bit CPU cycle counter (Labrosse, J. J. , 2010, p. 799).

All benchmark results are saved into a global array called `OSBenchmarks`, whose size is defined to be 10000. This array is accessed only by the benchmark code.

Listing 7.1 shows how the overhead of calling `OS_TS_GET()` is measured.

Listing 7.1: Benchmark Code for `OS_TS_GET()`

```
CPU_INT32U i;
for (i = 0; i < BENCHMARK_ARRAY_SIZE; ++i) {
    CPU_INT32U start = OS_TS_GET();
    CPU_INT32U measure = OS_TS_GET() - start;
    OSBenchmarks[i] = measure;
}
```

The call to `OS_TS_GET()` takes a constant amount of time, as shown in figure 7.1, as reading from a hardware register is very cheap.

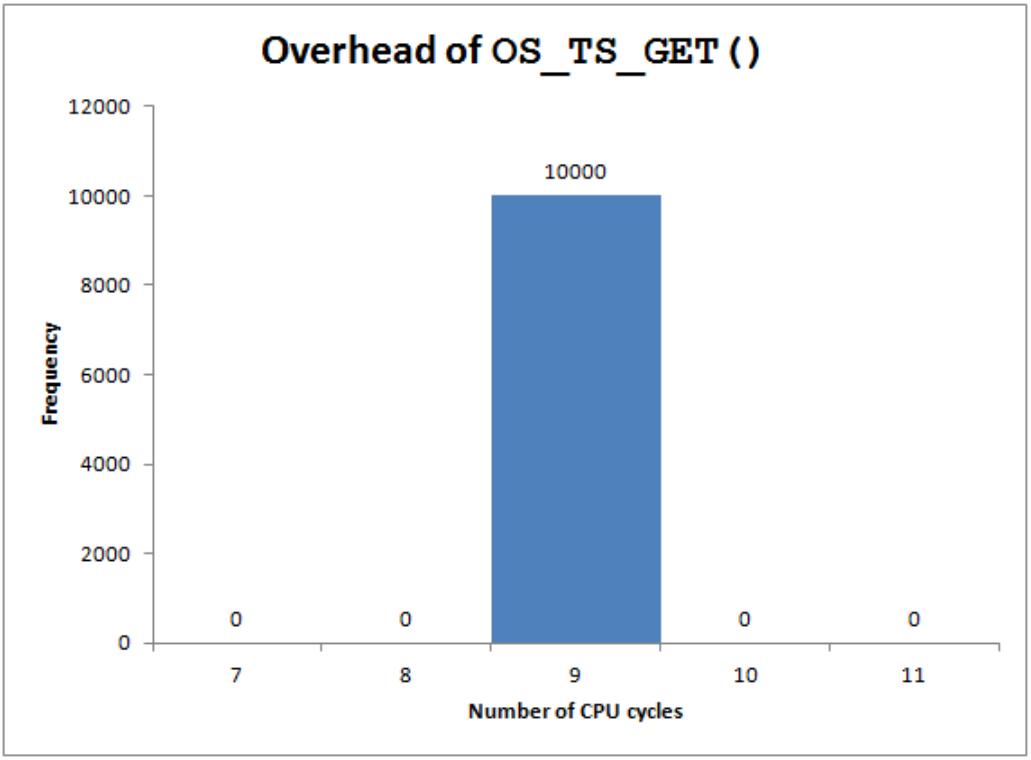

Figure 7.1: Overhead of `OS_TS_GET()`

In order to perform benchmarks, a helper macro, shown in listing 7.2, is defined for convenience.

Listing 7.2: Benchmark Helper

```
#define BENCHMARK(statement) do {                \
    CPU_INT32U start_b01 = OS_TS_GET();          \
    statement;                                   \
    CPU_INT32U measure_b01 =                     \
            OS_TS_GET() - start_b01;             \
    if (OSIndex < BENCHMARK_ARRAY_SIZE) {        \
      OSBenchmarks[OSIndex++] = measure_b01;     \
    }                                            \
} while(0)
```

For each function to be benchmarked, the original function is renamed to `original_benched`, e.g. `OSSched()` is renamed to `OSSched_benched()`, and a new function with the same name replaces the original function, with benchmark code wrapped around the call to the function to be benchmarked. Listing 7.3

shows how `OSSched()` is benchmarked.

Listing 7.3: Benchmarking `OSSched()`

```
void OSSched_benched (void)
{
    /* original code */
}

void OSSched (void)
{
    BENCHMARK(OSSched_benched());
}
```

The other functions are benchmarked in a similar manner.

7.2 Benchmarks and Evaluations

7.2.1 Scheduling

The tasks described in chapter 6 are used for benchmarking the scheduler.

Figure 7.2 shows the result of benchmarking `OSSched()`, which is the task level scheduler. The first spike at $0 - 100$ is due to `OSSched()` hitting the fast path, where the selected highest ready task is already the current task and no context switching is needed. The second spike at $48001 - 50000$ is due to the additional overhead of context switching to the new highest ready task.

Figure 7.3 shows the result of benchmarking `OSIntExit()`, which is the interrupt level scheduler. As interrupt service routines are designed to be very short in execution time, no context switching in `OSIntExit()` is encountered during the benchmarking process. The smaller spike in the data might be due to the book-keeping data already in CPU cache and no overhead of bringing them into cache is incurred.

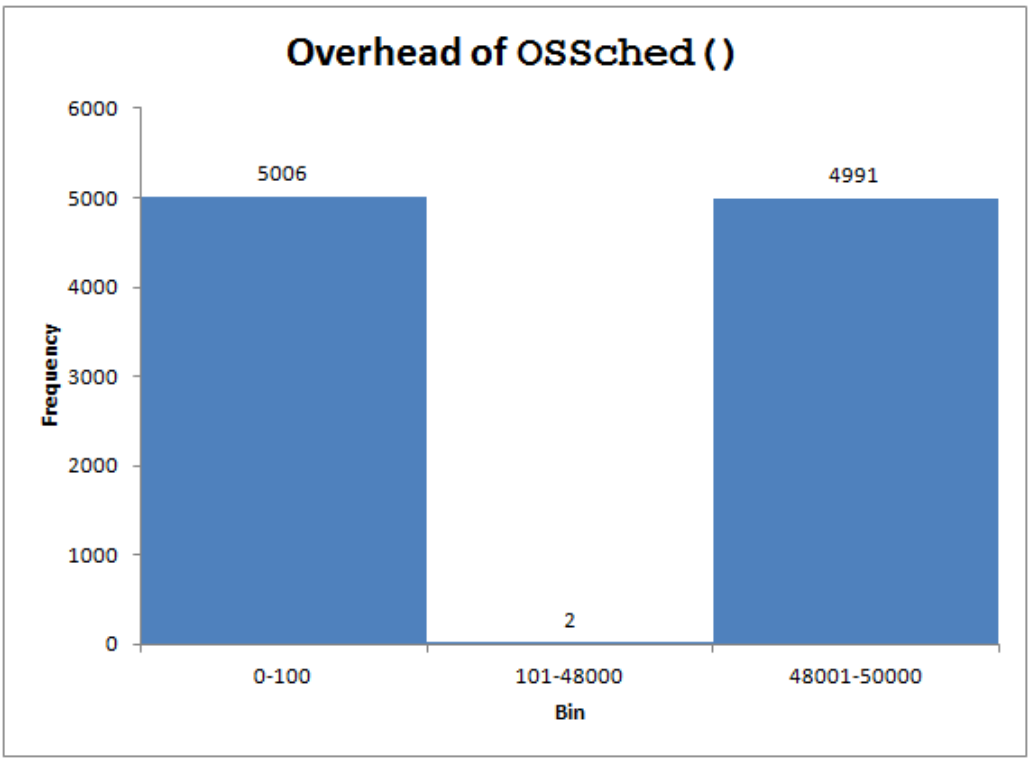

Figure 7.2: Overhead of `OSSched()`

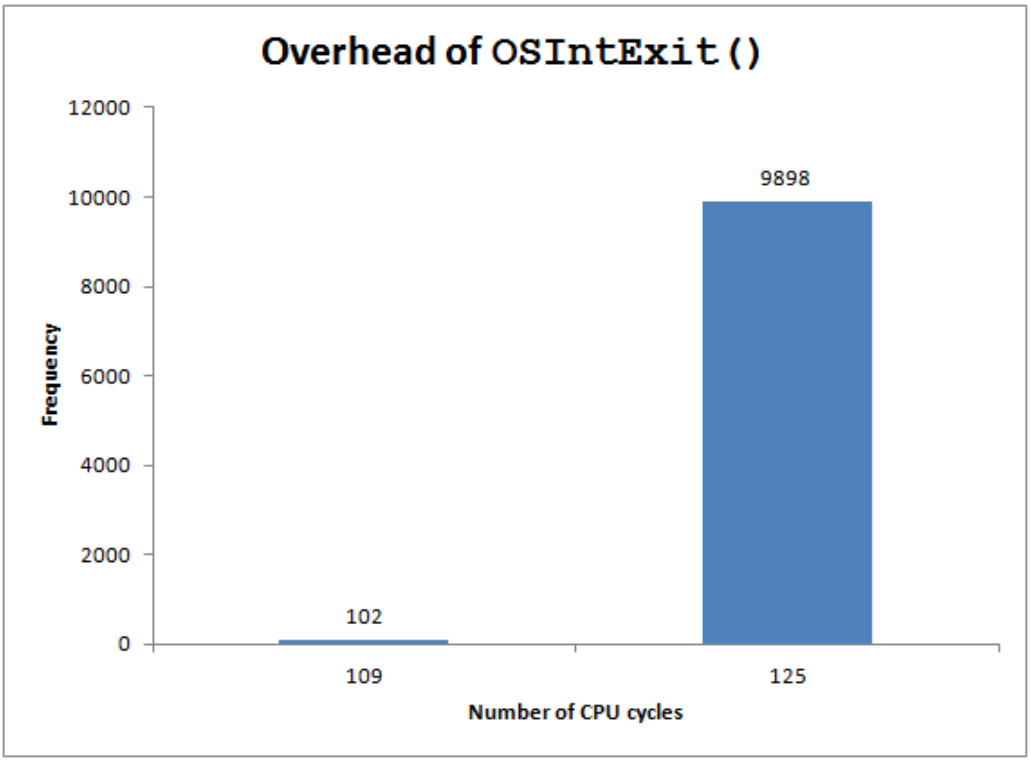

Figure 7.3: Overhead of `OSIntExit()`

7.2.2 Recurrent Task Spawner

Listing 7.4 shows a simple recurrent task with relative deadline of 8 milliseconds and period of 8 milliseconds which is used to benchmark the task spawner and `OSTaskDel()`.

Listing 7.4: A Simple Recurrent Task

```
void SimpleRecTask (void* p_arg)
{
    print instance number to LCD;
}
```

Figure 7.4 shows the results for benchmarking spawning a new task in the Task Spawner and figure 7.5 shows the results for benchmarking `OSTaskDel()`. As the two pieces of code are straight forward and the recurrent task does not make use of any advanced OS features, the running time is quite stable.

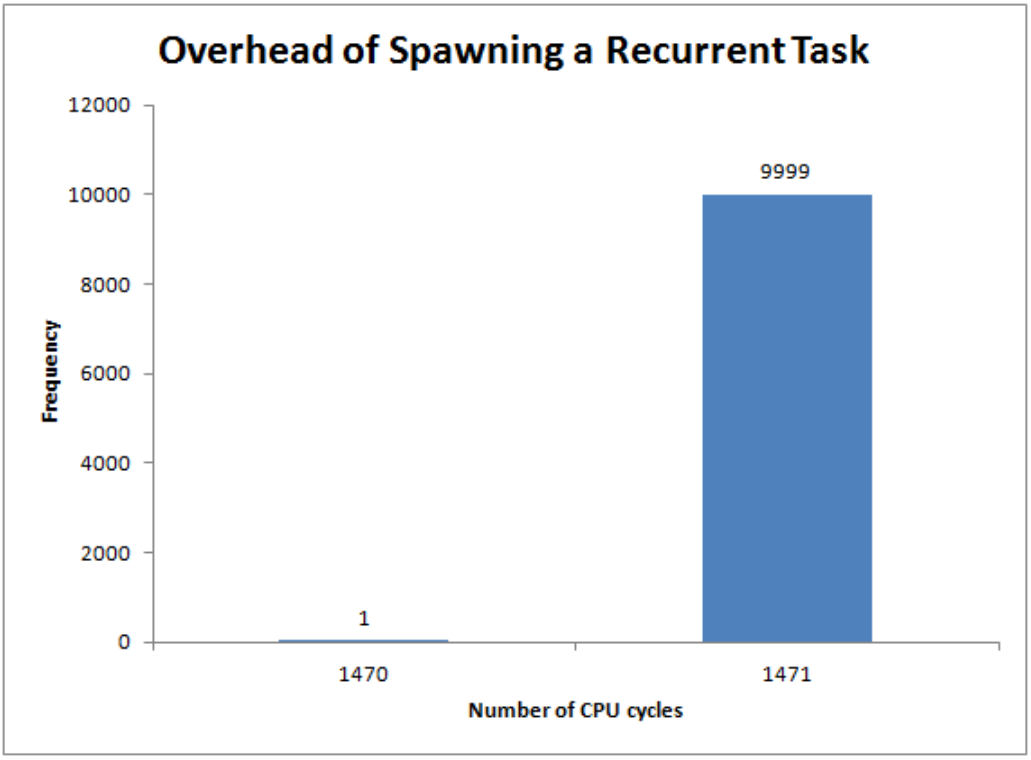

Figure 7.4: Overhead of Spawning a Recurrent Task

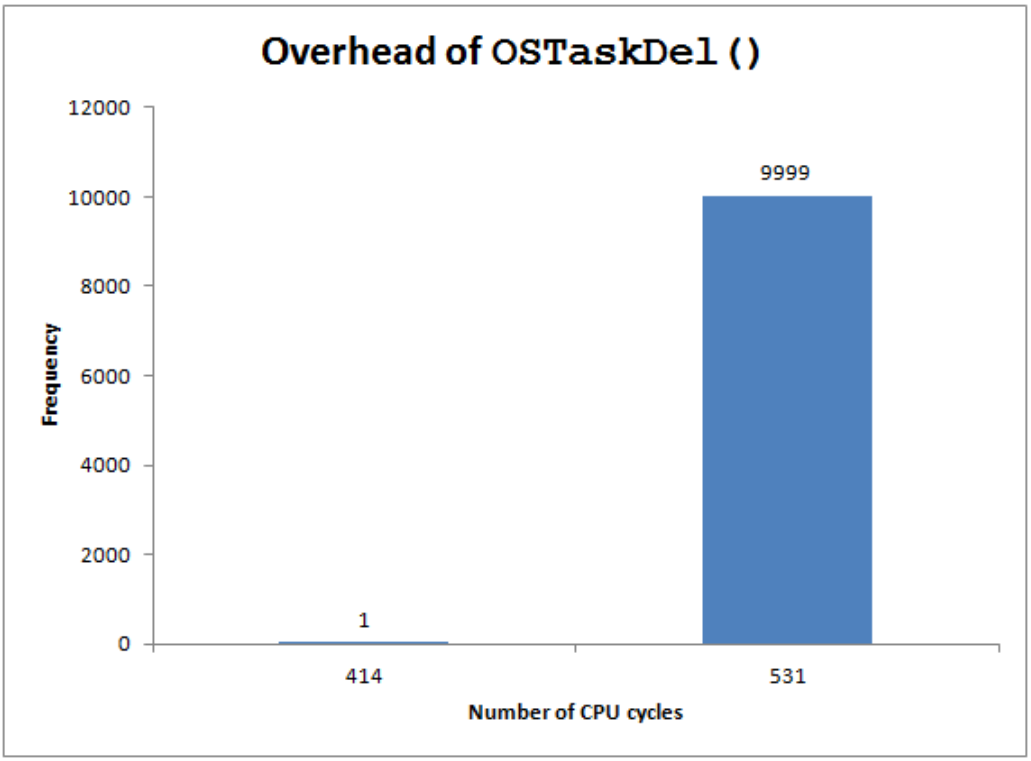

Figure 7.5: Overhead of `OSTaskDel()`

7.2.3 Mutex Operations

In order to benchmark mutex operations, two tasks which continually acquire and release two mutexes are run. Listing 7.5 shows the implementations of the two tasks.

Listing 7.5: Tasks to Benchmark Mutex Operations

```
void TaskOne (void* p_arg)
{
    loop forever {
        acquire mutex R1;
        acquire mutex R2;
        sleep for 10 milliseconds;
        release mutex R2;
        release mutex R1;
    }
}

void TaskTwo (void* p_arg)
{
    loop forever {
        acquire mutex R2;
        sleep for 10 milliseconds;
        acquire mutex R1;
        release mutex R1;
        release mutex R2;
    }
}
```

Figure 7.6 and figure 7.7 show results of benchmarking `OSMutexPend()` and `OSMutexPost()`, respectively. The higher numbers in the data might be due to contention in acquiring the mutexes or due to the overhead of bringing required data into cache.

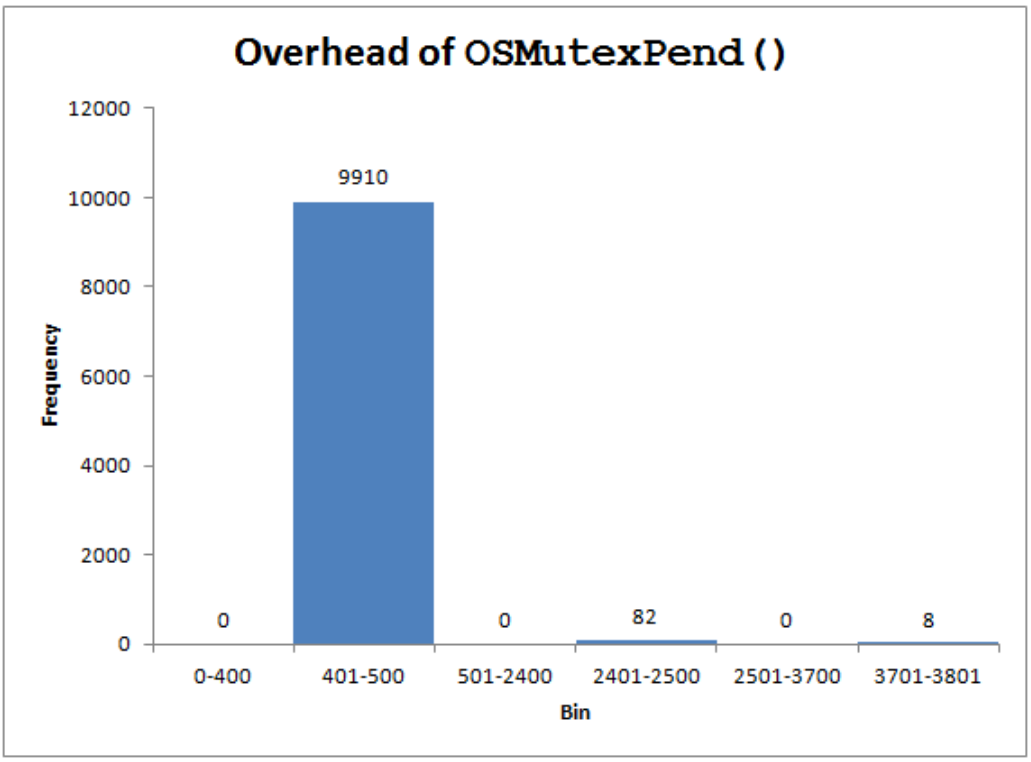

Figure 7.6: Overhead of `OSMutexPend()`

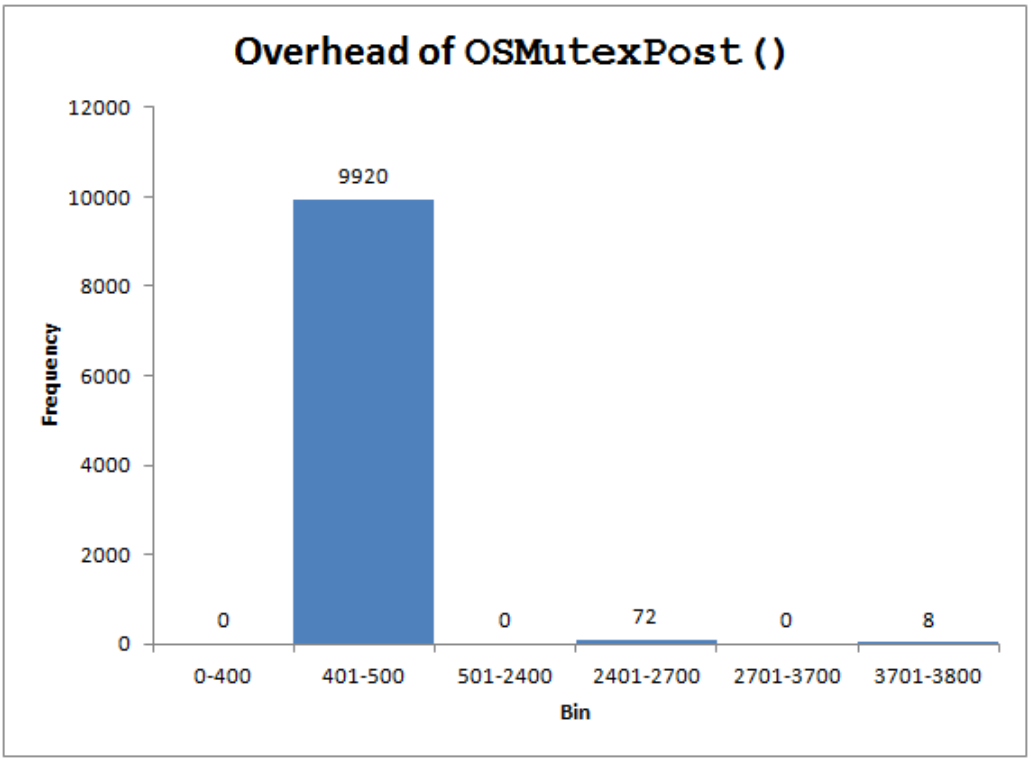

Figure 7.7: Overhead of `OSMutexPost()`

Chapter 8

Conclusion

In conclusion, several enhancements to Micrium μC/OS-III have been successfully implemented, namely recurrent tasks, a hybrid scheduler where earliest deadline first scheduling is run on top of fixed-priority scheduling, and priority ceiling protocol (PCP) for deadlock avoidance.

In the current implementation of PCP, each time a task acquires a mutex, the OS has to traverse the whole list of all created mutexes in order to find the system ceiling for the current task. Future research can attempt to improve performace of this calculation. One method is splitting that list into a list of mutexes which have owners, a list of mutexes which do not have owners but has tasks waiting on, and a list of all inactive mutexes.

Future research can also look into implementing pure earliest deadline first scheduling to replace the current hybrid scheduler. The author has attempted this method but failed to formulate how hardware interrupts can be handled as well as to overcome other nuances such as changing μC/OS-III's fundamental notion of priority as a fixed number.

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