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Dynamic frequency scheduling for CubeSat's on-board and data handling subsystem

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ABSTRACT

CubeSat is a small-sized satellite that provides a cheaper option for the manufacturer to have a fully operational satellite. Due to its size, CubeSat can only generate limited power, and this will restrict its functionality. This research aims to improve CubeSat's power consumption by implementing the dynamic voltage and frequency scaling (DVFS) technique to on-board and data handling subsystem (OBDH). DVFS will find the best operating frequency to execute all of OBDH's task. This paper explains how we determined the task set, representing all routine tasks performed by OBDH during normal operation mode. We have simulated the task set using two DVFS algorithms, static earliest deadline first (EDF) and cycle conserving edf (CC EDF). The result shows that both scheduling algorithms give a similar result to our task set. However, when the scheduler is configured as non-preemptive, the simulator failed to schedule the critical task. It means that the system fails to work as intended. Therefore, we conclude that we need to implement mixed-criticality scheduling to prevent critical tasks from being aborted by the system.

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1. INTRODUCTION

California polytechnic introduced CubeSat in 1999. It was initially used as an educational project to give students practical experience in satellite system engineering [1]. CubeSat's size varies from 1U (10x10x10 cm), 2U, 3U, 6U and as big as 27U (3Ux3Ux3U). It's small size allows developers to reduce components and launching costs [2]. After 20 years, more than 1000 CubeSats were launched into space. CubeSats are not only developed by academic institutions, but more than 50% of the CubeSats launched were developed by commercial sectors [3].

CubeSat provides an excellent platform to develop low-cost satellites, but it also has certain constraints that must be considered during the design and development phase. The size of CubeSat limits the size of solar arrays that can be mounted on its surface. 1U CubeSat can only have a maximum 100 cm^2 surface area to mount solar arrays on each side. Therefore, CubeSat can only generate a small amount of power from its solar panel. Besides that, CubeSat has minimal space for batteries that provide power to all subsystems due to its structure size. This situation restricts the developer from using high power consumption components and limits the CubeSat mission. A lot of research has been done to improve the power consumption of the CubeSat. They try to extend CubeSat's operational lifetime by improving the design of electrical power subsystems [4], [5] or introducing new hardware that can produce energy more efficiently [6]. There is also research focusing on the energy budget to help CubeSat developers select components efficiently based on their mission requirements [7].

This research aims to reduce the CubeSat's power consumption by focusing on task scheduling in on-board and data handling subsystem (OBDH). OBDH is the subsystem that controls all the processes and communicates with all subsystems in the CubeSat [8]. Even though OBDH typically consumes less power than other subsystems [9], it plays a vital role in managing processes or tasks. High power consumption tasks shall only be executed when required, and OBDH shall monitor battery levels before any scheduled task can be executed. In this research, a new energy-aware scheduling algorithm will be developed for OBDH. The algorithm is dynamic voltage and frequency scaling (DVFS) algorithm based on earliest deadline first (EDF) scheduling. In current OBDH design, there is no scheduling algorithm implemented. Therefore, we plan a few experiments to understand how it will affect the OBDH operation. This paper will report the experiment to identify the suitability of the algorithms using preemptive and non-preemptive scheduling for a task set that represents CubeSat’s operation. The experiment only chooses important task from each subsystem.

2. RESEARCH METHOD

On-board data handling subsystem (OBDH) is connected to all subsystems and manages all the processes or tasks as required. Figure 1 shows OBDH connects to the communications subsystem (COMS), electrical power subsystem (EPS), attitude determination and control subsystem (ADCS), thermal subsystem, and payload [10]. These subsystems may have sensors and actuators to give input to OBDH and allow it to make positional adjustments to achieve mission requirements.

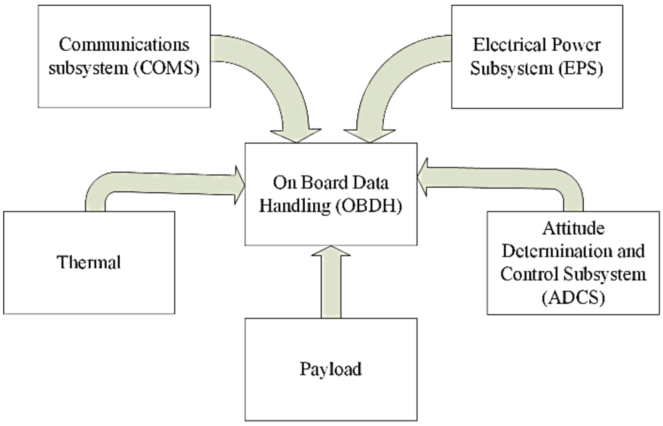

Figure 1. CubeSat's subsystems

COMS plays important rules to receive and transmit data between CubeSat and the ground station. OBDH will receive and decode commands from the ground and send telemetry and payload data back. These tasks are critical because, without command from the ground, CubeSat cannot execute its mission. EPS distributes power to all subsystems and ensures the CubeSat has enough power to continue operation until the end of its mission. OBDH will check the battery voltage and current supplied to all subsystems and store the data as housekeeping data [11].

ADCS is responsible for checking the orientation of the CubeSat and making corrections if necessary. It is a crucial subsystem if the mission requires pointing accuracy, such as an imaging mission. OBDH will ensure the camera is pointing in the right direction before an image can be taken. If not, OBDH will command ADCS to make the correction. ADCS is also used to stabilize the CubeSat in orbit.The thermal subsystem will continuously monitor the temperature of every subsystem. In orbit, CubeSat is exposed to the extreme hot and cold environment. Therefore, it is crucial to make sure the temperature is always within every component's operational temperature range. OBDH will monitor the temperature periodically, store it as housekeeping data, and take appropriate action if the temperature exceeds its limit.

CubeSat's payload is the subsystem that performs the function of the primary mission. For imaging missions, the payload can be a camera. The dosimeter can be a payload for a scientific mission, and antennas are a payload for a communication mission. OBDH must consider payload's task as one of the highest priority tasks to prevent data collected to become invalid or unusable.

Every task described above has different criticality and priority. The tasks also have different length of execution times, and some tasks can be preempted. Therefore, scheduling all the tasks are complex. For this research, tasks are selected based on mission operations, which are related to day-to-day activities [12]. The activities include bus operations (collecting housekeeping data), communications (transmitting data and receiving command), and payload operations (imaging).

To simplify the scheduling problem in this paper, few assumptions [13]-[15] are made as follows: i) All tasks are in normal operational mode; ii) All tasks are independent of other task and resources; iii) All tasks are periodic; iv) The task is aborted if it missed its deadlines; and v) CubeSat only communicates with only one ground station.

Tasks in this research are defined by four parameters: period, deadline, actual execution time (AET), and worst-case execution time (WCET) [16]. Value for every parameter is given based on general CubeSat operation [17]. Table 1 shows the selected tasks for this research and its parameters. The criticality of the task is also identified for the next phase of this research.

Table 1. Task set

Task	Details	Period/Deadline (ms)	AET (ms)	WCET (ms)	Criticality
T_1	Sensor (Thermal)	300	5	7	LOW
T_2	EPS	300	4	7	LOW
T_3	ADCS	100	20	25	LOW
T_4	Imaging (Payload)	500	1	2	HIGH
T_5	COMS	50	1	2	HIGH

The first task, T1, is to acquire reading from temperature sensors. Each subsystem will have at least one sensor. OBDH will obtain readings every 5 minutes. T2 is a task to get a battery voltage and current supplied to every subsystem. This task is essential to know how much is battery level and to detect anomalies on subsystems. The third task, T3, deals with attitude determination using the global positioning service (GPS) receiver. T4 and T5 are tasks involving capturing images and transmitting the image data and telemetry to the ground station. These tasks are categorized as high criticality tasks

Dynamic voltage and frequency scaling (DVFS) is a technique implemented at the operating system level to reduce power consumption during operation. The technique is dynamically adjusting the processor's voltage and frequency based on task execution time [18]. DVFS exploits the unused CPU times between WCET and Deadline, which is also known as slack. There are two types of slack: static and dynamic. Static slack is a usual slack, and dynamic slack is an interval between AET and WCET. Figure 2 shows the difference between static and dynamic slack.

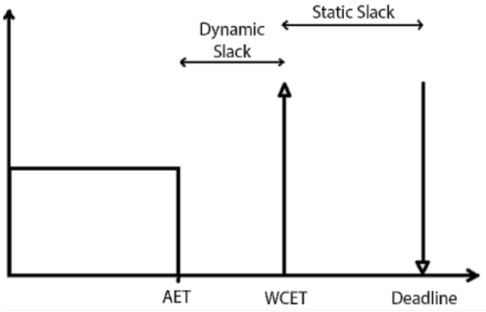

Figure 2. Static and dynamic slack

This experiment implements two DVFS algorithms based on the earliest deadline first (EDF) scheduling: Static EDF algorithm and cyclic cycle conserving EDF (CC EDF) algorithm [19]. Static EDF uses static slack to schedule the tasks. Based on the processor utilization of the task set, the minimum frequency will be determined. All task is executed at the same frequency.

On the other hand, CC EDF scales the frequency using dynamic slack. The first task will be executed based on its WCET. After the completion of the first task, if the task finishes before its WCET, the scheduler will transfer the remaining time to the next task. The frequency for the next task is scaled down based on the remaining time given. Figure 3 shows the difference between static EDF and CC EDF schedule for a similar task set.

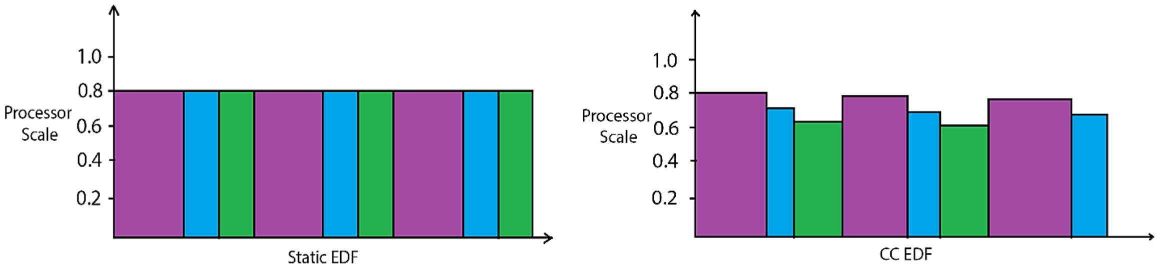

Figure 3. Static EDF and CC EDF scheduling

The task set was scheduled using two tools. The first tool is SimSo, an open-source software written in Python [20]. SimSo supports 25 schedulers for the uniprocessor and multiprocessor platform. It generates results in the form of a Gantt chart, which is easy to understand. Simso is used to simulate the task set as preemptive tasks. The second tool is a web-based simulator written in javascript. The scheduler in this simulator is based on the algorithm by Pillai [21]. This simulator will schedule the task set as a non-preemptive task.

DVFS algorithm is implemented on the processor that can run in multiple frequencies. In this research, we will use the STM32F7 microcontroller family. The processor has seven (7) frequency scaling [22], as shown in Table 2. We have scaled the processor speed based on the frequency. Even though the processor has seven speeds, in this simulation, only five (5), highest speed scale is used because the other two are too slow and will fail to schedule the task set. The simulation is done for 1500 ms and if any task misses its deadline, it will be aborted.

Table 1. Frequency scaling for STM32F7 microcontroller family

No.	Frequency (MHz)	Speed scale
1	216	1
2	200	0.93
3	180	0.83
4	168	0.78
5	144	0.67
6	60	0.28
7	25	0.11

3. RESULTS AND DISCUSSION

Figure 4 shows the simulation result for static EDF using SimSo. The scheduler utilized 100% of CPU time compared to the standard EDF scheduler [23], as shown in Figure 5. All task is executed at 0.67 processor speed which is the lowest speed set for the simulation. From the chart, we can observe that no task misses its deadline, and all task has longer execution time compared to their WCET. For example, T3 is run for 84 ms, more than three times longer than its WCET.

The result also shows that only T3 is not preempted because its execution time takes a long time and always imminent to its deadline. The situation is acceptable because task priority is based on a task that is near to its deadline. However, if the priority also considers the criticality of the task, the scheduler may have a problem to schedule this task set. In a real situation, T4 and T5 are critical tasks and should not be preempted. Next, we simulate the task set using CC EDF scheduler, and the result is similar to static EDF. This happened because the processor has a huge slack time, and 0.67 is the lowest speed scale set for simulation. Therefore, CC EDF does not provide a different result.

For non-preemptive task simulation, the JavaScript simulator fails to execute T4 and T5 for both types of schedulers. Both tasks are aborted after missing their deadlines when the processor speed is scaled at 0.67. This result shows that DVFS schedulers may have difficulties to schedule a non-preemptive task set successfully. From this simulation, we know that critical tasks are failed in non-preemptive scheduling. Therefore, our next phase in this research needs to include the criticality of the task to our consideration. We will look into the DVFS algorithm for mixed-criticality scheduling [24]. In mixed-criticality scheduling, non-critical tasks are allowed to miss their deadlines to allow critical tasks to meet their performance [25], [26].

We have not identified any suitable simulator for mixed-criticality scheduling, and hence we will do the development and test on the hardware. We are developing a prototype of a CubeSat using commercial of-the shelf (COTS) components with STM32F769 as a microcontroller for OBDH. FreeRTOS will be used as a real-time operating system to schedule the tasks in this research. DVFS algorithm will be implemented in its kernel, and we will trace the task execution using Segger systemview. By using hardware implementation, we can get a better result on the performance of the scheduler. In the simulation, we did not consider static power consumption, such as leakage power. Leakage power dissipation is also essential to be considered in microcontroller operations [27]. Therefore, testing on the prototype will allow us to understand more about dynamic and static power consumption.

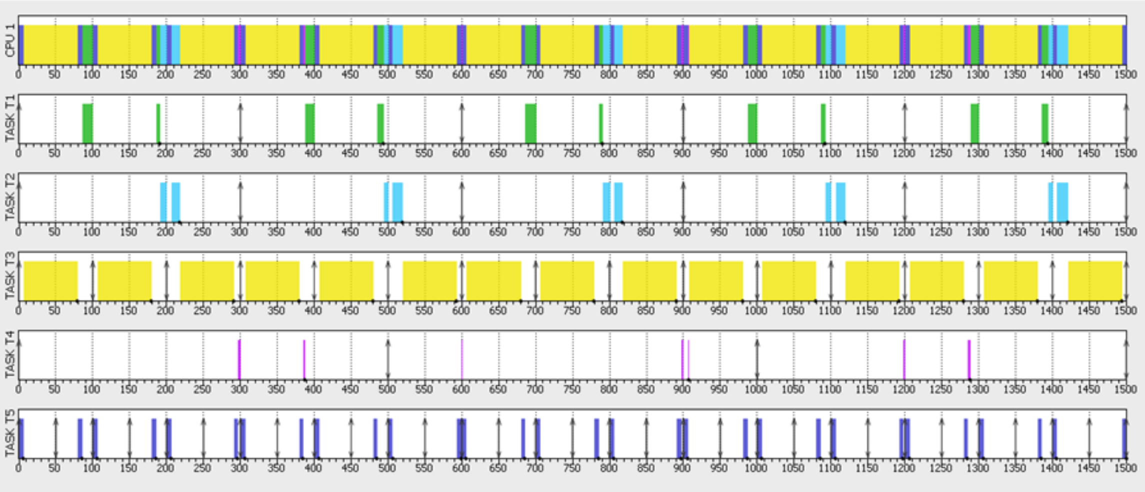

Figure 4. Static EDF simulation using SimSo

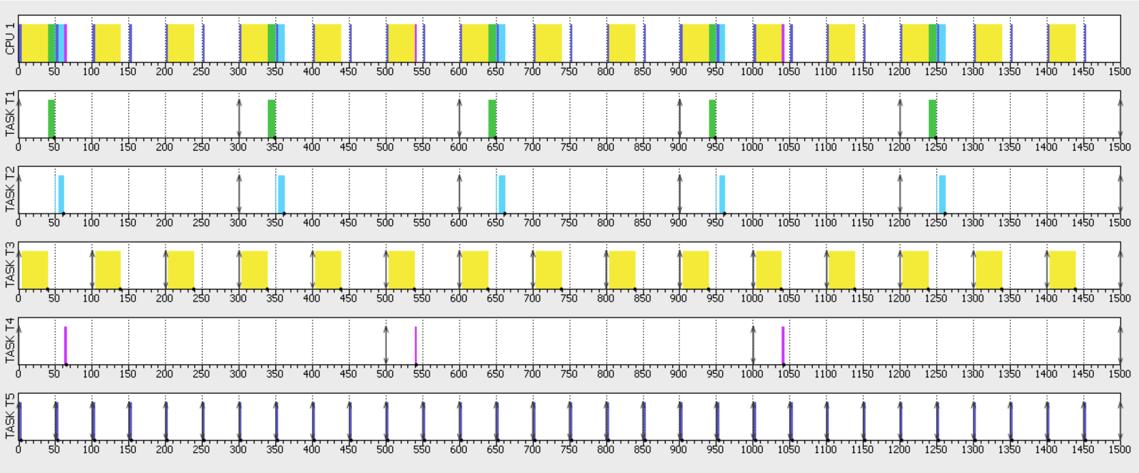

Figure 5. EDF simulation

4. CONCLUSION

This paper has explained our works on identifying suitable task set to represent significant operations of a CubeSat. The task set consists of a task from each subsystem. The simulation has covered two DVFS schedulers, static EDF, and CC EDF, for the preemptive and non-preemptive task. The result shows that it is no difference between both schedulers on the schedulability performance. The scheduler also failed to schedule critical tasks when we set the task set as non-preemptive. From this result, we understand that we need to consider task criticality as one of the scheduling parameters. We will implement mixed-criticality scheduling for this research. As a mixed-criticality system, CubeSat has multiple levels of task criticality: low-critical and mission-critical tasks. We will implement a new DVFS scheduler to a CubeSat's prototype that is being developed.

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