IIT Bombay

Seminar Report

on

Guaranteed Real-Time Control Methodologies Using Open-Source Tools

by

Sudhakar Kumar
Roll No. 183236001

Under the supervision of
Prof. Kannan Moudgalya
Department of Chemical Engineering
Indian Institute of Technology Bombay
Mumbai 400 076, INDIA

June 15, 2020

Contents

List of Figures

Chapter 1

Introduction

Commercial usage of computer dates back to a little more than 60 years. This brief period can roughly be divided into mainframe, PC, and post-PC eras of computing. The mainframe era was marked by expensive computers that were too expensive to be afforded by individuals, and each computer served a large number of users. Though the mainframes always outperformed PC, the PC era saw the revolutionary emergence of desktops which could easily be afforded and used by the individual users [1]. The post-PC era is a witness of the emergence of small and portable computers, and computers embedded in everyday applications, making an individual interact with several computers everyday [2].

Real-time and embedded computing applications in the first two computing eras (i.e., mainframe and PC) were rather rare and restricted to a few specialized applications such as space and defense. In the post-PC era of computing, the usage of computer systems based on real-time and embedded technologies has already touched every facet of our life and is still growing at an unprecedented pace. Several gadgets and applications which have today become indispensable to our every day life, are in fact based on embedded real-time systems. For example, we have pervasive consumer products such as digital cameras and cell phones; telecommunication domain products such as set-top boxes and video conferencing applications; office products such as fax machines, laser printers, and security systems. Besides, we encounter real-time systems in hospitals in the form of medical instrumentation equipment and imaging systems.

Some of the reasons which can be attributed to the remarkable growth in the usage of real-time systems lately are the manifold reductions in the size and the cost of the computers, coupled with the magical improvements to their performance. The availability of computers at rapidly falling prices, reduced weight, rapidly shrinking sizes, and their increasing processing power have together contributed to the present scenario. The rapid growth of applications deploying real-time technologies has been matched by the evolutionary growth of the underlying technologies supporting the development of real-time systems. In this report, we will discuss some of the technologies utilized in developing real-time systems, with restricting this discussion to the open-source tools which (can) guarantee the real-time control methodologies. The rest of the report is organized as follows.

In the second chapter on Real-Time Systems, we will define the concept of real-time and its comparison with respect to logical time. For a real-time system, if an answer i.e. the system's response to externally generated input stimuli is late, it's wrong. Thus, real-time systems are exploited to deal with the events where we cannot afford a delay of even one second. We will investigate the timing constraints for a real-time system along with its applications in industry, defense, aerospace, etc. Subsequently, a basic model, along with its important functional blocks, of a real-time system is presented. Next, we discuss the key characteristics of real-time systems, which must be met while dealing with these systems. At the end of this chapter on Real-Time Systems, we explain the hard real-time tasks, firm real-time tasks, and soft real-time tasks.

In the third chapter on Real-Time Task Scheduling, we will discuss the available scheduling algorithms for real-time tasks. The two main types of schedulers are: clock-driven and event-driven. Along with these two types, we discuss their sub-types briefly. We will have a look at the comparison between clock-driven scheduling and event-driven scheduling. Along with these two traditional scheduling algorithms, we will study two important dynamic scheduling algorithms which have been immensely useful in real-time sensing and control systems. Dynamic scheduling is a method in which the hardware determines which instructions to execute, as opposed to a statically scheduled machine, in which the compiler determines the order of execution.

In the fourth chapter on Real-Time Operating Systems (RTOS), we examine the important features that an RTOS is expected to support. Here, we discuss the key features which are quintessential for an RTOS and are usually missing in a General Purpose Operating System (GPOS). Along with this, we elaborate the concept of multitasking and context switching. Next, we investigate whether Unix or Windows qualify for an RTOS. The traditional Unix operating system suffers from several shortcomings when used in real-time applications. Windows NT has several features which are very desirable for real-time applications such as support for multi-threading, real-time priority levels, and timer. However, it is neither advisable nor feasible to use NT for hard real-time applications, for example, at the controller level with sub-millisecond precision. At the end of this chapter, we summarize the major differences between a GPOS and an RTOS.

In the fifth chapter on Tools for enabling Real-Time Features, we explain some of the open-source tools which are being utilized to enable real-time constraints across various platforms like an operating system, open-source software like Scilab, OpenModelica, and micro-controllers like Arduino. For enabling Linux as a real-time system, we describe three important patches/extensions namely, PREEMPT_RT, RTLinux, and RTAI. With RTAI-Lab and Scilab, it is possible to obtain a complete open source environment for designing control systems and test them in real physical systems. This software tool-chain is equivalent to the proprietary software for control systems Labview or Dspace. Next, we will discuss two tools available in OpenModelica – Modelica.`StateGraph` and Real-Time simulation flag – which can be used to characterize reactive systems and the physical time concept of real-time systems. We will show how real-time flag in OpenModelica enforces the quantitative notion of time. Next, we create a task of blinking two LEDs at different rates using FreeRTOS on Arduino Uno. Finally, we present a discussion on when and where we should use FreeRTOS.

Chapter 2

About Real-Time Systems

Real-time is a quantitative notion of time. Real-time is measured using a physical (real) clock. Whenever we quantify time using a physical clock, we deal with real-time. For instance, let us consider an automated chemical plant. When the temperature of the chemical reaction chamber attains a certain predetermined temperature, say 250°C, the system automatically switches off the heater within a predetermined time interval, say within 30 milliseconds. In this description of a part of the behavior of a chemical plant, the time value that was referred to denotes the readings of some physical clock present in the plant automation system.

In contrast to real-time, logical time (also known as virtual time) deals with a qualitative notion of time and is expressed using event ordering relations. While dealing with logical time, time readings from a physical clock are not necessary for ordering the events. As an example, consider the following part of the behavior of library automation software used to automate the book-keeping activities of a college library: "After a query book command is given by the user, details of all matching books are displayed by the software." In this example, the events "issue of query book command" and "display of results" are logically ordered in terms of which events follow the other. But, no quantitative expression of time was required. Clearly, this example behavior is devoid of any real-time considerations.

A real-time system changes its state as a function of physical time, e.g., a chemical reaction continues to change its state even after its controlling computer system has stopped [3]. Based on this a real-time system can be decomposed into a set of subsystems i.e., the controlled object, the real-time computer system and the human operator, as shown in figure 2.1. A real-time computer system must react to stimuli from the controlled object (or the operator) within time intervals dictated by its environment. The instant at which a result is produced is called a deadline.

A system is called a real-time system, when we need quantitative expression of time (i.e. real-time) to describe the behavior of the system. In other words, a real-time system is any information processing system which has to respond to externally generated input stimuli within a finite and specified timing constraint [4]. In these systems,

- Correctness of the system behavior depends not only on the logical results of the computations, but also on the physical instant at which these results are produced.
- Failure to respond in time is as bad as the wrong response!

Thus, the key thing to remember about a real-time system is that in a real-time system if an answer is late, it's wrong. Since we are in PC era, all of us use a PC (with different operating systems) every now and then. One can argue that all operating systems are real-time. That is, they all have some kind of deadline. According to Steven Rostedt (a Linux kernel developer at

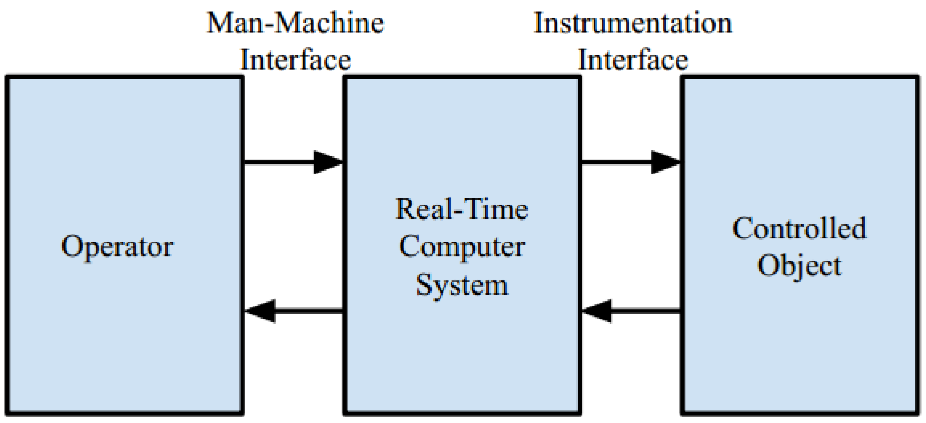


Figure 2.1: Real-Time Systems

Red Hat and maintainer of the stable version of the real-time Linux kernel patch), if we hit a key and the computer does not respond in say 5 minutes, we are likely to throw the computer out the window [5]. It failed to meet its deadline. When our deadlines are big enough, pretty much any operating system will do.

Let us say, we are plotting a series of data on a GPOS on a PC. Ideally, we should expect our PC to generate the plot in a couple of seconds (like 2-3 seconds). However, we won't mind even if this operation is delayed by one more second as there's no real impact of this delay. On the other hand, consider the event of plotting the series of data vis-à-vis applying a brake in a car, where the delay of even one second could be catastrophic. Thus, real-time systems are exploited to deal with such events where we cannot afford a delay of even one second.

2.1 Applications of Real-Time Systems

There are quite a few applications of real-time systems in wide ranging areas. In the following subsections, we list some of the prominent areas like industries, defense, aerospace, etc. where real-time systems are extensively exploited.

2.1.1 Industrial Applications

Chemical Plant Control

Chemical plant control systems are essentially a type of process control application. In an automated chemical plant, a real-time computer periodically monitors plant conditions. The plant conditions are determined based on current readings of pressure, temperature, and chemical concentration of the reaction chamber. These parameters are sampled periodically. Based on the values sampled at any time, the automation system decides on the corrective actions necessary at that instant to maintain the chemical reaction at a certain rate. Each time the plant conditions are sampled, the automation system should decide on the exact instantaneous corrective actions required such as changing the pressure, temperature, or chemical concentration and carry out these actions within certain predefined time bounds. Typically, the time bounds in such a chemical plant control application range from a few micro seconds to several milliseconds.

Automated Car Assembly Plant

In an automated car assembly plant, the work product (partially assembled car) moves on a conveyor belt, as shown in figure 2.2. By the side of the conveyor belt, several workstations are placed. Each workstation performs some specific work on the work product such as fitting engine, fitting door, fitting wheel, etc. as it moves on the conveyor belt. An empty chassis is introduced near the first workstation on the conveyor belt. A fully assembled car comes out after the work product goes past all the workstations. At each workstation, a sensor senses the arrival of the next partially assembled product. As soon as the partially assembled product is sensed, the workstation begins to perform its work on the work product. The time constraint imposed on the workstation computer is that the workstation must complete its work before the work product moves away to the next workstation. The time bounds involved here are typically of the order of a few hundreds of milliseconds.

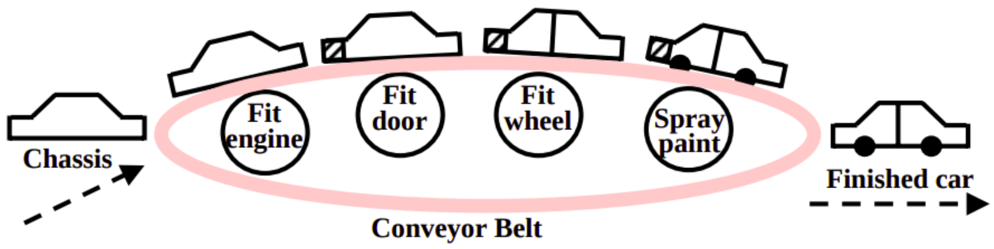


Figure 2.2: Schematic Representation of an Automated Car Assembly Plant

Supervisory Control and Data Acquisition (SCADA)
A SCADA system helps monitor and control a large number of distributed events of interest. In SCADA systems, sensors are scattered at various geographic locations to collect raw data (called events of interest). These data are then processed and stored in a real-time database. The database models (or reflects) the current state of the environment. The database is updated frequently to make it a realistic model of the up-to-date state of the environment. An example of a SCADA system is a system that monitors and controls traffic in a computer network. Depending on the sensed load in different segments of the network, the SCADA system makes the router change its traffic routing policy dynamically. The time constraint in such a SCADA application is that the sensors must sense the system state at regular intervals (say every few milliseconds) and the same must be processed before the next state is sensed.

2.1.2 Defense Applications

Missile Guidance System
A guided missile is capable of sensing the target and homes onto it. In a missile guidance system, missile guidance is achieved by a computer mounted on the missile. The mounted computer computes the deviation from the required trajectory and affects track changes of the missile to guide it onto the target. The time constraint on the computer-based guidance system is that the sensing and the track correction tasks must be activated frequently enough to keep the missile from diverging from the target. The target sensing and track correction tasks are typically required to be completed within a few hundreds of microseconds or even lesser time depending on the speed of the missile and the type of the target.

2.1.3 Aerospace

Computer On-board an Aircraft
In a modern aircraft, the pilot can select an “auto pilot” option. As soon as the pilot switches to the “auto pilot” mode, an on-board computer takes over all controls of the aircraft including navigation, take-off, and landing of the aircraft. In the “auto pilot” mode, the computer periodically samples velocity and acceleration of the aircraft. From the sampled data, the on-board

computer computes X, Y, and Z co-ordinates of the current aircraft position and compares them with the pre-specified track data. Before the next sample values are obtained, it computes the deviation from the specified track values and takes any corrective actions that may be necessary. In this case, the sampling of the various parameters, and their processing need to be completed within a few micro seconds.

Now, we summarize the average time bound for all the above mentioned applications, as given in the table 2.1. It would help us understand the timing requirements for a real-time system. In the previous section, we discussed that when our deadlines are big enough, any operating system will serve as a real-time system.

Applications	Time bound
Chemical plant control	few microseconds to several milliseconds
Automated car assembly plant	few hundreds of milliseconds
SCADA	few milliseconds
Missile guidance system	few hundreds of milliseconds
Computer on-board an aircraft	few micro seconds

Table 2.1: Applications of Real-Time Systems with its Time Bound

From the table 2.1, we can infer that in case of real-time systems, the time bound ranges from a few microseconds to a few milliseconds. Adding to this, a delay in the response might lead to an untoward situation.

2.2 Basic Model of a Real-Time System

The figure 2.3 shows a simple model of a real-time system in terms of its important functional blocks. Here, the sensors are interfaced with the input conditioning block, which in turn is connected to the input interface. The output interface, output conditioning, and the actuator are interfaced in a complementary manner. The figure 2.3 can be easily related with the figure 2.1. Now, we briefly describe the roles of the different functional blocks given in figure 2.3.

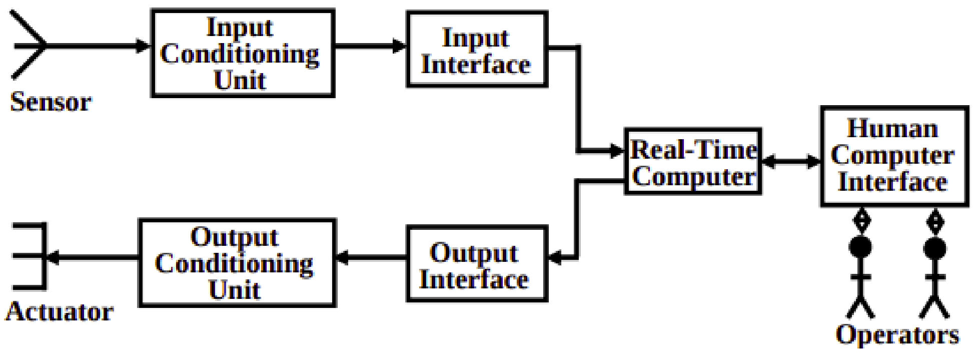


Figure 2.3: Model of a Real-Time System

- **Sensor**: It converts some physical characteristic of its environment into electrical signals. An example of a sensor is a photo-voltaic cell which converts light energy into electrical energy.

- **Actuator**: An actuator is any device that takes its inputs from the output interface of a computer and converts these electrical signals into some physical actions on its environment. The physical actions may be in the form of motion, change of thermal, electrical, or physical characteristics of some objects. A popular actuator is a motor.

- **Signal Conditioning Units**: The electrical signals produced by a computer can rarely be used to directly drive an actuator. The computer signals usually need before they can be used by the actuator. This is termed as output conditioning. Similarly, input conditioning is also required to be carried out on sensor signals before they can be accepted by the computer. For example, analog signals generated by a photo-voltaic cell are normally in the milli-volts range and need to be conditioned before they can be processed by a computer. Some important conditioning techniques are voltage amplification, voltage level shifting, signal mode conversion, etc.

- **Interface Unit**: Normally commands from the CPU are delivered to the actuator through an output interface. An output interface converts the stored voltage into analog form and then outputs this to the actuator circuitry. This of course would require the value generated to be written on a register, as shown in figure 2.4.

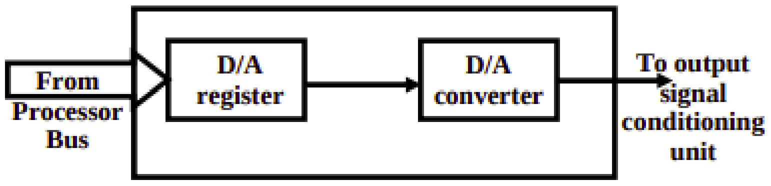


Figure 2.4: Output Interface (from CPU to an actuator)

2.3 Characteristics of Real-Time Systems

We now discuss a few key characteristics of real-time systems, which distinguish real-time systems from non-real-time systems.

- **Time constraints**: Every real-time task is associated with some time constraints. One very common form of time constraints is deadlines associated with tasks. A task deadline specifies the time before which the task must complete and produce the results. It is the responsibility of the RTOS to ensure that all tasks meet their respective time constraints.

- **Correctness Criterion**: The notion of correctness in real-time systems is different from that used in the context of traditional systems. In real-time systems, correctness implies not only logical correctness of the results, but the time at which the results are produced is important. A logically correct result produced after the deadline would be considered as an incorrect result.

- **Concurrency**: A real-time system usually needs to respond to several independent events within very short and strict time bounds. For instance, consider the chemical plant control, discussed in section 2.1.1, which monitors the progress of a chemical reaction and controls the rate of reaction by changing the different parameters of reaction such as pressure, temperature, etc. These parameters are sensed using sensors fixed in the chemical reaction chamber. These sensors may generate data asynchronously at different rates. Therefore, the real-time system must process data from all the sensors concurrently, otherwise signals may be lost and the system may malfunction.

- **Custom Hardware**: A real-time system is often implemented on custom hardware that is specifically designed and developed for the purpose. For example, a cell phone does not use traditional microprocessors. Cell phones use processors which are tiny, supporting only those processing capabilities that are really necessary for cell phone operation and specifically designed to be power-efficient to conserve battery life. Another example is the embedded processor in an Multi-Point Fuel Injection (MPFI) car. In this case, the processor used need not be a powerful general purpose processor such as a Pentium processor. Some of the most powerful computers used in MPFI engines are 16 or 32-bit processors running at approximately 40 MHz. However, unlike the conventional PCs, a processor used in these car engines do not deal with processing frills such as screen-savers or a dozen of different applications running at the same time.

- **Reactive**: Real-time systems are often reactive. A reactive system is one in which an ongoing interaction between the computer and the environment is maintained. Ordinary systems compute functions on the input data to generate the output data, as given in figure 2.5. In other words, traditional systems compute the output data as some function ϕ of the input data.

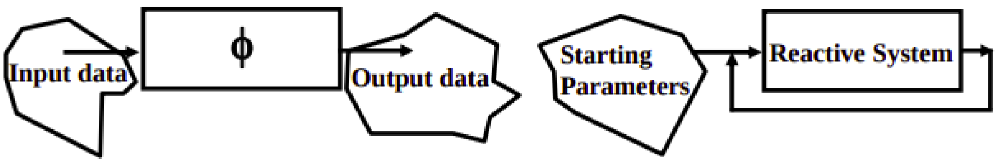


Figure 2.5: Traditional (left) versus Reactive (right) Systems

In contrast to traditional systems, real-time systems do not produce any output data but enter into an ongoing interaction with their environment. In each interaction step, the results computed are used to carry out some actions on the environment. The reaction of the environment is sampled and is fed back to the system. We will get back to reactive systems again while discussing the library `StateGraph` [6], which is used to model discrete event and reactive systems by hierarchical state machines in OpenModelica.

- **Stability**: Under overload conditions, real-time systems need to continue to meet the deadlines of the most critical tasks, though the deadlines of non-critical tasks may not be met. This is in contrast to the requirement of fairness for traditional systems even under overload conditions.

- **Exception Handling**: Many real-time systems work round-the-clock and often operate without human operators. For example, consider a small automated chemical plant that is set up to work non-stop. When there are no human operators, taking corrective actions on a failure becomes difficult. Even if no corrective actions can be immediate taken, it is desirable that a failure does not result in catastrophic situations. A failure should be detected and the system should continue to operate in a gracefully degraded mode rather than shutting off abruptly.

2.4 Classification of Real-Time Systems

Depending on the consequences of a task missing its deadline, a real-time task can be classified into three main types namely Hard real-time tasks, Firm real-time tasks, and Soft real-time tasks.

2.4.1 Hard Real-Time Tasks

A hard real-time task is one that is constrained to produce its results within certain predefined time bounds. The system is considered to have failed whenever any of its hard real-time tasks does not produce its required results before the specified time bound.

An example of a system having hard real-time tasks is a robot. The robot cyclically carries out a number of activities including communication with the host system, logging all completed activities, sensing the environment to detect any obstacles present, tracking the objects of interest, path planning, etc. Now consider that the robot suddenly encounters an obstacle. The robot must detect it and as soon as possible try to escape colliding with it. If it fails to respond to it quickly (i.e. the concerned tasks are not completed before the required time bound), then it would collide with the obstacle and the robot would be considered to have failed. Therefore detecting obstacles and reacting to it are hard real-time tasks.

For hard real-time tasks in practical systems, the time bounds usually range from several microseconds to a few milliseconds. It may be noted that a hard real-time task does not need to be completed within the shortest time possible, but it is merely required that the task must complete within the specified time bound.

2.4.2 Firm Real-Time Tasks

Every firm real-time task is associated with some predefined deadline before which it is required to produce its results. However, unlike a hard real-time task, even when a firm real-time task does not complete within its deadline, the system does not fail. The late results are merely discarded. In other words, the utility of the results computed by a firm real-time task becomes zero after the deadline. The figure 2.6 schematically shows the utility of the results produced by a firm real-time task as a function of time. For firm real-time tasks, the associated time bounds typically range from a few milliseconds to several hundreds of milliseconds. Firm real-

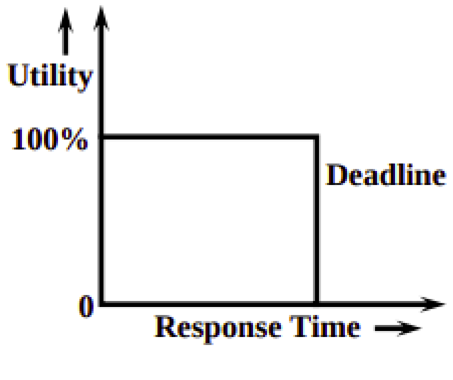


Figure 2.6: Utility of Result of a Firm Real-Time Task with Time

time tasks typically abound in multimedia applications, such as video conferencing. Another example of firm real-time task could be satellite-based tracking of enemy movements.

2.4.3 Soft Real-Time Tasks

Unlike hard and firm real-time tasks, the timing constraints on soft real-time tasks are not expressed as absolute values. Instead, the constraints are expressed either in terms of the average response times required.

Another example of a soft real-time task is handling request for seat reservation in railway reservation application. Once a request for reservation is made, the response should occur within 20 seconds on the average. The response may either be in the form of a printed ticket or an apology message on account of unavailability of seats. Alternatively, we might state the constraint on the ticketing task as: At least in case of 95% of reservation requests, the ticket should be processed and printed in less than 20 seconds.

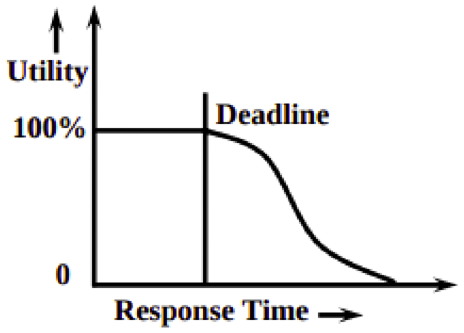


Figure 2.7: Utility of Result of a Soft Real-Time Task with Time

Let us now analyze the impact of the failure of a soft real-time task to meet its deadline, by taking the example of the railway reservation task. If the ticket is printed in about 20 seconds, we feel that the system is working fine and get a feel of having obtained instant results. As we have discussed, missed deadlines of soft real-time tasks do not result in system failures. However, the utility of the results produced by a soft real-time task falls continuously with time after the expiry of the deadline as shown in figure 2.7. For soft real-time tasks that typically occur in practical applications, the time bounds usually range from a fraction of a second to a few seconds. Now, we will summarize the major differences between hard and soft real-time tasks, as given in the table 2.2.

Characteristics	**Hard Real-Time**	**Soft Real-Time**
Response time	Hard-required	Soft-desired
Peak load performance	Predictable	Degraded
Control of pace	Environment	Computer
Safety	Often critical	Non-critical
Size of data files	Small/medium	Large
Error detection	Autonomous	User assisted
Time bound	microseconds to few milliseconds	few seconds

Table 2.2: Comparison of Hard Real-Time Tasks and Soft Real-Time Tasks

Chapter 3

Real-Time Task Scheduling

Real-time task scheduling essentially refers to determining the order in which the various tasks are to be taken up for execution by the operating system. Every operating system relies on one or more task schedulers to prepare the schedule of execution of various tasks it needs to run. Each task scheduler is characterized by the scheduling algorithm it employs. Here, we will discuss the available scheduling algorithms.

3.1 Types of Real-Time Task Scheduling Algorithms

The two main types of schedulers are: clock-driven and event-driven. Furthermore, these two schedulers are classified into different subtypes, as given below:

1. Clock-driven – Table-driven and Cyclic
2. Event-driven – Simple priority based, Earliest Deadline First (EDF), and Rate Monotonic Analysis (RMA)

3.1.1 Clock-Driven Scheduling

Clock-driven schedulers make their scheduling decisions regarding which task to run next only at the clock interrupt points. Clock-driven schedulers are those for which the scheduling points are determined by timer interrupts. These schedulers are also known as off-line schedulers because these schedulers fix the schedule before the system starts to run. That is, the scheduler predetermines which task will run when. Therefore, these schedulers incur very little run time overhead. However, a prominent shortcoming of this class of schedulers is that they can not satisfactorily handle aperiodic and sporadic (one that recurs at random instants) tasks since the exact time of occurrence of these tasks can not be predicted. For this reason, this type of schedulers is also called static scheduler.

There are two important clock-driven schedulers: table-driven and cyclic schedulers. Table-driven schedulers usually pre-compute which task would run when, and store this schedule in a table at the time the system is designed or configured. On the other hand, a cyclic scheduler repeats a pre-computed schedule. The pre-computed schedule needs to be stored only for one major cycle.

3.1.2 Event-Driven Scheduling

Unlike cyclic schedulers, event-driven schedulers can handle aperiodic and sporadic tasks more proficiently. On the flip side, event-driven schedulers are less efficient as they deploy more complex scheduling algorithms. Therefore, event-driven schedulers are less suitable for embedded applications as these are required to be of small size, low cost, and consume minimal amount of power. Next, we discuss the three important types of event-driven schedulers.

A foreground-background scheduler is possibly the simplest priority-driven preemptive scheduler. In foreground-background scheduling, the real-time tasks in an application are run as foreground tasks. The sporadic, aperiodic, and non-real-time tasks are run as background tasks. Among the foreground tasks, at every scheduling point the highest priority task is taken up for scheduling. A background task can run when none of the foreground tasks is ready. In other words, the background tasks run at the lowest priority.

In EDF scheduling, at every scheduling point the task having the shortest deadline is taken up for scheduling. EDF has been proven to be an optimal uni-processor scheduling algorithm. This means that, if a set of tasks is not schedulable under EDF, then no other scheduling algorithm can feasibly schedule this task set.

Parameter	**Clock-Driven Scheduling**	**Event-Driven Scheduling**
Scheduling points	Timer interrupts	Events precluding clock interrupts
Design	Simple & efficient	More sophisticated
Tasks	Periodic	Sporadic, aperiodic, and periodic
Applications	Embedded systems	Moderate and large-sized applications
Scheduling	Offline	Online

Table 3.1: Comparison of Clock-Driven Scheduling and Event-Driven Scheduling

RMA, another important event-driven scheduling algorithm, is extensively used in practical applications. It assigns priorities to tasks based on their rates of occurrence. The lower the occurrence rate of a task, the lower is the priority assigned to it. A task having the highest occurrence rate (lowest period) is accorded the highest priority. Now, we will have a look at the comparison between clock-driven scheduling and event-driven scheduling, as shown in the table 3.1 [7].

3.2 Dynamic Scheduling

Dynamic scheduling is a method in which the hardware determines which instructions to execute, as opposed to a statically scheduled machine, in which the compiler determines the order of execution. Here, we discuss some of the important dynamic scheduling algorithms.

3.2.1 Deferrable Scheduling with Least Actual Laxity First

In real-time sensing and control systems, there is a need to monitor the Quality of Data (QoD) along with the Quality of Control (QoC). Keeping a track of QoD will let us know whether the sensor data has become stale. On the other hand, by following the QoC, we can check whether the deadline constraints of control transactions are fulfilled. There will always be a trade-off between maintaining the quality of real-time data objects and fulfilling the deadline constraints of control transactions while ensuring both QoD and QoC.

A dynamic scheduling algorithm named Deferrable Scheduling with Least Actual Laxity First (DS-LALF) is proposed in [9] to maintain the validity of real-time data objects. The actual laxity of a job is a measure of the spare time the job has before it misses its deadline – by considering the time needed for higher priority jobs to be executed. In DS-LALF, control transactions are assigned lower priorities compared with the update transactions. Thus, it will maximize the QoD while affecting the schedulability of control transactions.

An extension of the algorithm DS-LALF, named Co-LALF is presented to resolve the co-scheduling problem between update and control transactions in a real-time sensing and control system. The goal of Co-LALF is to construct a schedule that can meet the deadlines of all the periodic control transactions and can maximize the QoD as well.

3.2.2 Improving QoC using Flexible Timing Constraints

As the closed-loop control systems are subject to perturbations, there is a need to design controllers to correct or limit the deviation caused by transient perturbations in the controlled system response. Though such controllers have been implemented using fixed timing constraints (sampling period and time delay), it prevents the controllers to execute dynamically, which in turn implies the wastage of resources when the system is in equilibrium along with quick reaction to perturbations.

A controller with flexible timing constraints is presented in [10] which allows the design of discrete-time controllers depending upon a finite set of values for the sampling period and on a finite set of values for the time delay. The flexible timing constraints for control tasks are defined in the form of a set of EXAST (EXAct start time Separation constrainT) values and a set of EXACT (EXAct start-to-Completion time-interval constrainT). The former refers to the set of sampling period values, whereas the latter refers to the set of time delays' values. The controller is designed with this assumption that the sampling will occur at (i.e., not after) EXAST and the actuation will complete at (i.e., not before) EXACT.

By selecting specific EXAST and EXACT values, the control task instance execution can be enabled to adapt according to the system dynamics. It means that when the controlled system response deviates due to perturbations, we will be able to speed up the execution of the controller in order to minimize such deviations, and when perturbations are not affecting the system, we can slow down the controller execution rate in order to save resources.

Chapter 4

Concepts in Real-Time Operating Systems

Real-time operating systems are primarily responsible for ensuring that every real-time task meets its timeliness requirements. An RTOS in turn achieves this by using appropriate task scheduling techniques, which we have discussed in the previous chapter. Normally RTOSes provide flexibility to the programmers to select an appropriate scheduling policy among several supported policies. Deployment of an appropriate task scheduling technique out of the supported techniques is therefore an important concern for every real-time programmer. In this chapter, we examine the important features that an RTOS is expected to support. We start by discussing the features of an RTOS followed by the issues that would arise if we attempt to use a general purpose operating system such as UNIX or Windows in real-time applications.

4.1 Features of an RTOS

We identify some important features required for an RTOS, and especially those that are normally absent in a GPOS.

- **Clock and Timer Support**: Clock and timer services with adequate resolution are one of the most important issues in real-time programming. Hard real-time application development often requires support of timer services with resolution of the order of a few microseconds. And even finer resolution may be required in case of certain special applications. On the other hand, a GPOS often does not provide time services with sufficiently high resolution.

- **Real-Time Priority Levels**: An RTOS must support static priority levels. A priority level supported by an operating system is called static, when once the programmer assigns a priority value to a task, the operating system does not change it by itself. Static priority levels are also called real-time priority levels. On the other hand, all traditional operating systems dynamically change the priority levels of tasks to maximize system throughput.

- **Fast Task Preemption**: For successful operation of a real-time application, whenever a high priority critical task arrives, an executing low priority task should be made to instantly yield the CPU to it. The time duration for which a higher priority task waits before it is allowed to execute is quantitatively expressed as the corresponding task preemption time. Contemporary RTOS has task preemption times of the order of a few micro seconds. However, in a GPOS, the worst case task preemption time is usually of the order of a second. Thus, an RTOS needs to have a preemptive kernel and should have task preemption times of the order of a few micro seconds.

- **Predictable and Fast Interrupt Latency**: Interrupt latency is defined as the time delay between the occurrence of an interrupt and the running of the corresponding interrupt service routine (ISR). In an RTOS, the upper bound on interrupt latency must be bounded and is expected to be less than a few micro seconds. This is especially important for hard real-time applications with sub-microsecond timing requirements.

4.2 RTOS Fundamentals

Here, we present an introduction to real-time and multitasking concepts [11].

- **Multitasking**: Each executing program is a task (or thread) under control of the operating system. If an operating system can execute multiple tasks in this manner it is said to be multitasking. A conventional processor can only execute a single task at a time – but by rapidly switching between tasks a multitasking operating system can make it appear as if each task is executing concurrently. This is depicted in the figure 4.1 which shows the execution pattern of three tasks with respect to time. The task names are color coded and written down the left hand.

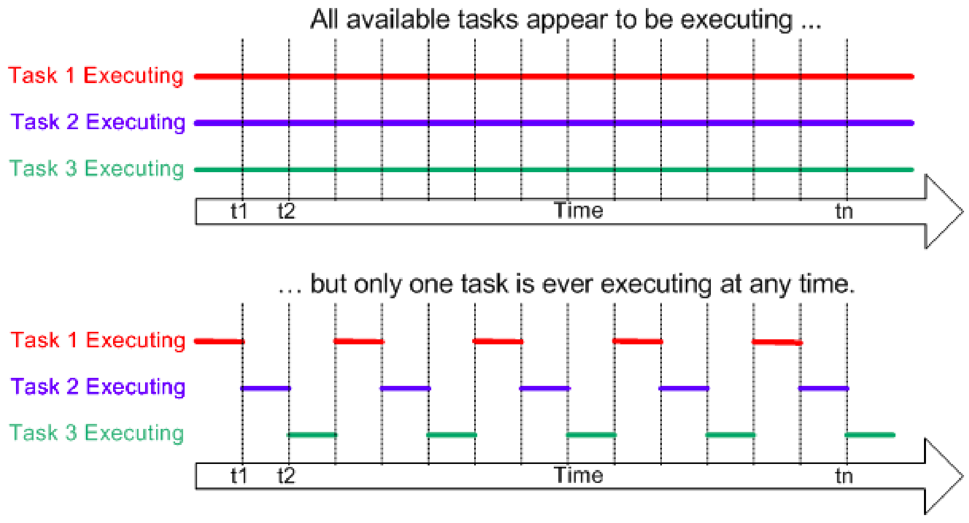


Figure 4.1: Multitasking Vs Concurrency

- **Scheduling**: The scheduler is the part of the kernel responsible for deciding which task should be executing at any particular time. The kernel can suspend and later resume a task many times during the task lifetime. The scheduling policy is the algorithm used by the scheduler to decide which task to execute at any point in time. The policy of a (non real-time) multi user system will most likely allow each task a "fair" proportion of processor time.

- **Context Switching**: As a task executes, it utilizes the processor/micro-controller registers and accesses RAM and ROM just as any other program. These resources together (the processor registers, stack, etc.) comprise the task execution context.

  A task is a sequential piece of code – it does not know when it is going to get suspended (swapped out or switched out) or resumed (swapped in or switched in) by the kernel and does not even know when this has happened. Consider the example of a task being suspended immediately before executing an instruction that sums the values contained within two processor registers. While the task is suspended other tasks will execute and may modify the processor register values. Upon resumption the task will not know that the processor registers have been altered – if it used the modified values the summation would result in an incorrect value.

To prevent this type of error it is essential that upon resumption a task has a context identical to that immediately prior to its suspension. The operating system kernel is responsible for ensuring this is the case – and does so by saving the context of a task as it is suspended. When the task is resumed its saved context is restored by the operating system kernel prior to its execution. The process of saving the context of a task being suspended and restoring the context of a task being resumed is called context switching.

4.3 Unix as an RTOS

Unix is a popular GPOS that was originally developed for the mainframe computers. Since Unix and its variants are inexpensive and are now widely available, it is worthwhile to investigate whether Unix can be used in real-time applications. The traditional Unix operating system suffers from several shortcomings when used in real-time applications. A few of these have been discussed below.

- **Non-Preemptive Kernel**: One of the biggest problems that real-time programmers face while using Unix for real-time application development is that Unix kernel cannot be preempted. That is, all interrupts are disabled when any operating system routine runs.

  A process running in kernel mode cannot be preempted by other processes. In other words, the Unix kernel is non-preemptive. On the other hand, the Unix system does preempt processes running in the user mode. A consequence of this is that even when a low priority process makes a system call, the high priority processes would have to wait until the system call completes. The longest system calls may take up to several hundreds of milliseconds to complete.

- **Dynamic Priority Levels**: In Unix systems real-time tasks can not be assigned static priority values. Soon after a programmer sets a priority value, the operating system alters it. This makes it very difficult to schedule real-time tasks using algorithms such as RMA or EDF, since both these schedulers assume that once task priorities are assigned, it should not be altered by any other parts of the operating system.

4.4 Windows as an RTOS

Microsoft's Windows operating systems have evolved over the years from the naive DOS (Disk Operating System). As several new versions of Windows kept on appearing by way of upgrades, the Windows code was completely rewritten in 1998 to develop the Windows NT system. Since the code was completely rewritten, Windows NT system was much more stable than the earlier DOS-based systems. The later versions of Microsoft's operating systems were descendants of the Windows NT. Here, we consider only the Windows NT and its descendants.

Windows NT has several features which are very desirable for real-time applications such as support for multi-threading, real-time priority levels, and timer. Moreover, the clock resolutions are sufficiently fine for most real-time applications. Windows NT supports 32 priority levels. Each process belongs to one of the following priority classes: idle, normal, high, real-time. By default, the priority class at which an application runs is normal. NT uses priority-driven preemptive scheduling and threads of real-time priorities have precedence over all other threads including kernel threads.

In spite of the impressive support that Windows provides for real-time program development as discussed above, it is neither advisable nor feasible to use NT for hard real-time applications, for example, at the controller level with sub-millisecond precision [12]. NT may still be useful for applications that can tolerate occasional deadline misses, and have delay/response time requirements in the tens to hundreds of milliseconds range. At the end, we present a comparison of the extent to which some of the basic features required for real-time programming are provided by Windows NT and Unix V, as given in the table 4.1.

Real-Time Features	**Windows NT**	**Unix V**
DPCs	Yes	No
Real-Time priorities	Yes	No
Locking virtual memory	Yes	Yes
Timer precision	1 msec	10 msec
Asynchronous I/O	Yes	No

Table 4.1: Windows NT versus Unix

Next, we also summarize the major differences between a GPOS and an RTOS [13], as given in the table 4.2.

GPOS	**RTOS**
Used for desktop PC and laptop.	Used for the embedded applications.
Process-based Scheduling	Time-based scheduling
Interrupt latency not important	Interrupt lag is minimal (in microseconds)
Kernel's operation may or may not be preempted	Kernel's operation can be preempted.

Table 4.2: Differences between a GPOS and an RTOS

Chapter 5

Tools for enabling Real-Time Features on Various Platforms

In this chapter, we will explain some of the open-source tools which are being utilized to enable real-time constraints across various platforms like an operating system, open-source software like Scilab [14], OpenModelica [15], and micro-controllers like Arduino [16].

We will begin our discussion with POSIX, which stands for Portable Operating System Interface. "X" has been suffixed to the abbreviation to make it sound Unix-like. Over the last decade, POSIX has become an important standard in the operating systems area including real-time operating systems. The importance of POSIX can be evaluated from the fact that nowadays it has become uncommon to come across a commercial operating system that is not POSIX-compliant. POSIX started as an open software initiative.

5.1 Linux as a Real-Time System

Here, we discuss some of the important patches or extension like PREEMPT_RT, RTLinux, RTAI, etc. which make Linux into a real-time system.

5.1.1 PREEMPT_RT

The PREEMPT_RT patch (aka the -rt patch or RT patch) makes Linux into a real-time system [5]. If our embedded device has some "must have" deadlines to respond to then the PREEMPT_RT patch would probably be sufficient. What PREEMPT_RT gives us over the normal kernel is not only faster response times, but more importantly, it removes all unbounded latency. An unbounded latency is where the amount of delay that can occur is dependent on the situation. For example, with unfair reader writer locks, where the writer has to wait for there to be no readers before it can take the lock. Because new readers can continually take the lock at any time while the writer is waiting, the writer may never get the lock. This is a prime example of an unbounded latency on the writer.

According to Steven Rostedt (a Linux kernel developer at Red Hat and maintainer of the stable version of the real-time Linux kernel patch), PREEMPT_RT is really good enough for robotics, stock exchanges, and for computers that have to interface with the "Hard" real-time software.

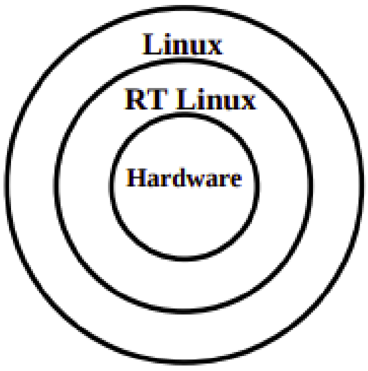


Figure 5.1: Structure of RTLinux

5.1.2 Real-Time Linux (RTLinux)

RTLinux runs along with a Linux system [17]. The real-time kernel sits between the hardware and the Linux system, as shown in the figure 5.1. The RT kernel intercepts all interrupts generated by the hardware. If an interrupt is to cause a real-time task to run, the real-time kernel preempts Linux, if Linux is running at that time, and lets the real-time task run. Thus, in effect Linux runs as a task of RTLinux.

The real-time applications are written as loadable kernel modules. In essence, real-time applications run in the kernel space. In the approach taken by RT Linux, there are effectively two independent kernels: real-time kernel and Linux kernel. Therefore, this approach is also known as the dual-kernel approach as the real-time kernel is implemented outside the Linux kernel. Any task that requires deterministic scheduling is run as a real-time task. These tasks preempt Linux whenever they need to execute and yield the CPU to Linux only when no real-time task is ready to run.

Compared to the micro-kernel approach, the following are the shortcomings of the dual-kernel approach.

- **Duplicated Coding Efforts**: Tasks running in the real-time kernel can not make full use of the Linux system services – file systems, networking, and so on. In fact, if a real-time task invokes a Linux service, it will be subject to the same preemption problems that prohibit Linux processes from behaving deterministically. As a result, new drivers and system services must be created specifically for the real-time kernel – even when equivalent services already exist for Linux.

- **Fragile Execution Environment**: Tasks running in the real-time kernel do not benefit from the memory management unit (MMU)-protected environment that Linux provides to the regular non-real-time processes. Instead, they run unprotected in the kernel space. Consequently, any real-time task that contains a coding error such as a corrupt C pointer can easily cause a fatal kernel fault. This is serious problem since many embedded applications are safety-critical in nature.

- **Limited Portability**: In the dual-kernel approach, the real-time tasks are not Linux processes at all; but programs written using a small subset of POSIX APIs. To aggravate the matter, different implementations of dual-kernels use different APIs. As a result, real-time programs written using one vendor's RT-Linux version may not run on another vendor.

- **Programming Difficulty**: RT-Linux kernels support only a limited subset of POSIX APIs. Therefore, application development takes more effort and time.

5.1.3 Real-Time Application Interface (RTAI) for Linux

RTAI (https://www.rtai.org/) is a real-time extension for the Linux kernel, which lets users write applications with strict timing constraints for Linux [18] [19]. Like Linux itself the RTAI software is a community effort. RTAI provides deterministic response to interrupts, POSIX-compliant and native RTAI real-time tasks. RTAI supports several architectures, including x86-64, ARM, and MIPS.

RTAI consists mainly of two parts: an Adeos-based patch to the Linux kernel which introduces a hardware abstraction layer, and a broad variety of services which make lives of real-time programmers easier. Adeos is a kernel patch comprising an interrupt pipeline where different operating system domains register interrupt handlers [20]. This way, RTAI can transparently take over interrupts while leaving the processing of all others to Linux.

5.1.4 Subtle Differences between RTAI and RTLinux

Here, we investigate the subtle differences while using RTAI vis-à-vis RTLinux in real-time implementations. Prof. Paolo Mantegazza started the RTAI project based on Victor Yodaiken's RTLinux v. 1 [17]. Since then, RTLinux and RTAI have gone through long development paths on their own. Despite the fact that they're not API-compatible, their functionalities are very similar [21]. All key primitives and services exist in both packages. Both offer:

- A small real-time core
- One-shot and periodic timer support
- Real-time scheduler
- Real-time threads
- Real-time FIFOs and shared memory
- Real-time interrupt handler

Thus, RTAI provides a more practical API while RTLinux is more elegant. On the other hand, RTAI is more elegant in how it integrates into the Linux kernel. The RTAI team makes a constant effort to add features that people ask for, and thus its API has grown to become reasonably extensive. For example, RTAI includes clock (8254 and APIC) calibration, dynamic memory management for realtime tasks, LXRT (Linux Extension for Real-Time) to bring soft/hard real-time capabilities into user space, remote procedure calls, and mailboxes. Due to the practicality of RTAI API, an open source project named RTAI-Lab aims to provide a common structure framework for the integration of RTAI into the Scilab environment [22]. With RTAI-Lab and Scilab, it is possible to obtain a complete open source environment for designing control systems and test them in real physical systems. This software tool-chain is equivalent to the proprietary software for control systems Labview or Dspace.

The RTLinux team aims to keep their real-time Linux extensions as predictable as possible, adding only features that won't hurt designs and compatibility in the future. In short, the RTLinux API is more consistent, but many practitioners prefer to use RTAI.

5.2 OpenModelica for Real-Time Systems

OpenModelica [15] is an open-source Modelica-based modeling and simulation environment intended for industrial and academic usage. The goal with the OpenModelica effort is to create a comprehensive Open Source Modelica modeling, compilation and simulation environment based on free software distributed in binary and source code form for research, teaching, and industrial usage. In this section, we present two tools available in OpenModelica – Modelica.`StateGraph` and Real-Time simulation flag – which can be used to characterize reactive systems and the physical time concept of real-time systems.

5.2.1 Modelica.StateGraph

Modelica is primarily a modeling language that allows specification of mathematical models of complex natural or man-made systems, for example, for the purpose of computer simulation of dynamic systems where behavior evolves as a function of time [23]. Modelica is also an object-oriented, equation-based programming language, oriented toward computational applications with high complexity requiring high performance.

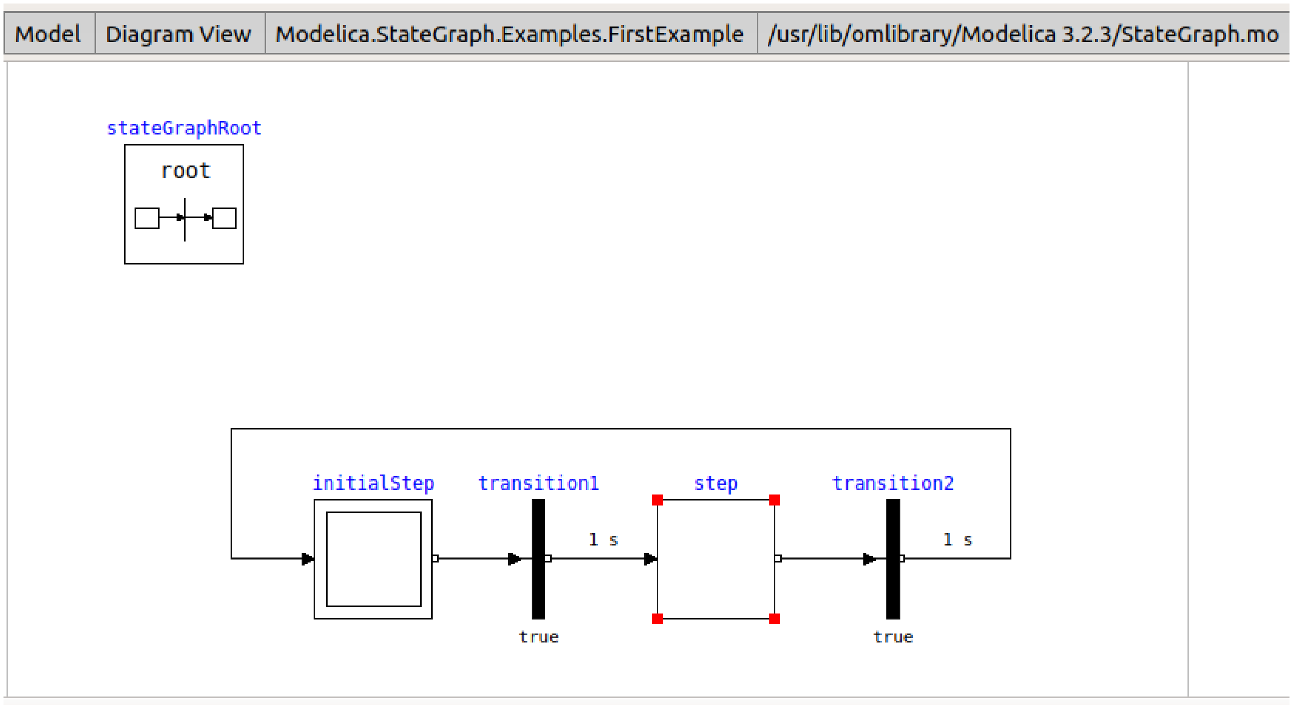

Model
Diagram View
Modelica.StateGraph.Examples.FirstExample
/usr/lib/omlibrary/Modelica 3.2.3/StateGraph.mo
stateGraphRoot
root
initialStep
transition1
step
transition2
1 s
1 s
true
true

Figure 5.2: Basic Example of `StateGraph` in OpenModelica

Modelica modeling formalism matches all the requirements for characterizing reactive systems, as discussed in section 2.3. For instance, concurrency is natural since modeled objects evolve concurrently over time. Time aspects can be efficiently modeled, and specified behavior is deterministic. Since Modelica is a declarative formalism, models should hopefully be somewhat amenable to formal verification techniques for enhancing reliability. Modeled subsystems can be realized as efficient implementations of reactive computer systems that interact directly with the physical environment in real-time. Alternatively, both the reactive system and the surrounding physical environment can be modeled and simulated. A third alternative is to mix simulated subsystems with hardware components, that is, hardware-in-the-loop simulation [24].

Library `StateGraph` is a free Modelica package providing components to model discrete event and reactive systems in a convenient way [6]. It is based on the JGrafchart method and takes advantage of Modelica features for the “action” language. JGrafchart is a further development of Grafcet to include elements of StateCharts that are not present in Grafcet/Sequential Function Charts. Therefore, the `StateGraph` library has a similar modeling power as StateCharts but avoids some deficiencies of StateCharts.

A basic example of `StateGraph` is shown in the figure 5.2. In JGrafcharts, Grafcet, Sequential Function Charts and StateCharts, actions are formulated within a step. Such actions are distinguished as entry, normal, exit and abort actions. For example, a valve might be opened by an entry action of a step and might be closed by an exit action of the same step. `StateGraph`, this is not possible due to Modelica’s “single assignment rule” that requires that every variable is defined by exactly one equation. For example, via the “SetBoolean” component, the valve variable is set to true when the `StateGraph` is in particular steps.

This feature of a `StateGraph` is very useful, since it allows a Modelica translator to guarantee that a given `StateGraph` has always deterministic behaviour without conflicts. In the other methodologies this is much more cumbersome. For example, if two steps are executed in parallel and both step actions modify the same variable, the result is either non-deterministic or non-obvious rules have to be defined which action takes priority. In a `StateGraph`, such a situation is detected by the translator resulting in an error, since there are two equations to compute one variable.

5.2.2 Simulation Flags in OpenModelica

Apart from `StateGraph` library, we can use a simulation flag for real-time synchronization in OpenModelica [25]. This flag can be enabled by using `-rt=value` or `-rt value`. The value specifies the scaling factor for real-time synchronization (0 disables). A value greater than 1 means the simulation takes a longer time to simulate. For our study, we simulated a first order

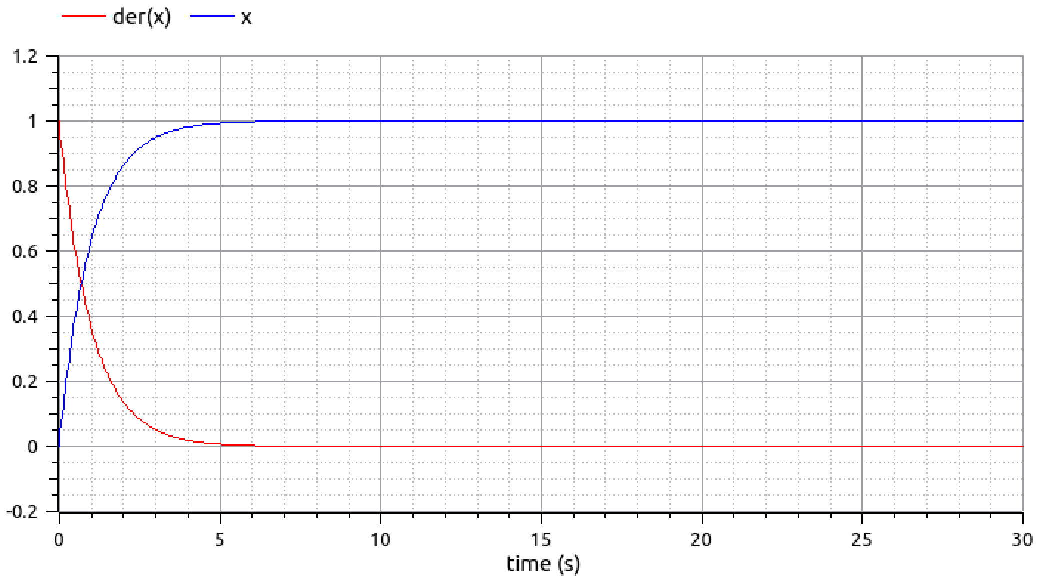


Figure 5.3: Simulation of a First-Order System in OpenModelica

model by enabling the real-time flag. It was observed that with flag enabled, the simulation takes physical time into consideration, as discussed in second chapter. Thus, the real-time simulation for the exact duration of the simulation. The output of the simulation is as shown in the figure 5.3 and the video of the simulation is available on YouTube.

5.3 FreeRTOS Task Implementation in Arduino IDE

FreeRTOS is a class of RTOS for embedded devices which is small enough to be run on 8/16-bit micro-controllers, although its use is not limited to these micro-controllers [26]. It is open-source and it's code is available on GitHub (https://github.com/FreeRTOS).

As FreeRTOS can run on 8-bit MCU so it can also be run on Arduino Uno board. We have to just download the FreeRTOS library and then start implementing the code using APIs. We will consider an example of blinking two LEDs at different rates on an Arduino Uno using FreeRTOS. For this example, we will consider the following tasks:

- LED blink at Digital pin 8 with 200ms frequency.
- LED blink at Digital pin 7 with 300ms frequency.
- Print numbers in serial monitor with 500ms frequency.

According to the FreeRTOS structure, we will include the Arduino FreeRTOS header file. Then we need to make function prototypes. As we have three tasks, so we will make three functions and it's prototypes, as given below:

```
    #include <Arduino_FreeRTOS.h>
    void TaskBlink1(void *pvParameters);
    void TaskBlink2(void *pvParameters);
    void Taskprint(void *pvParameters);
```

In `void setup()` function, we will initialize serial communication at 9600 bits per second and create all three tasks using `xTaskCreate()` API of FreeRTOS. Initially, we will make the priorities of all tasks as '1' and start the scheduler.

```
    void setup() {
    Serial.begin(9600);
    xTaskCreate(TaskBlink1, "Task1", 128, NULL, 1, NULL);
    xTaskCreate(TaskBlink2, "Task2 ", 128, NULL, 1, NULL);
    xTaskCreate(Taskprint, "Task3", 128, NULL, 1, NULL);
    vTaskStartScheduler();
}
```

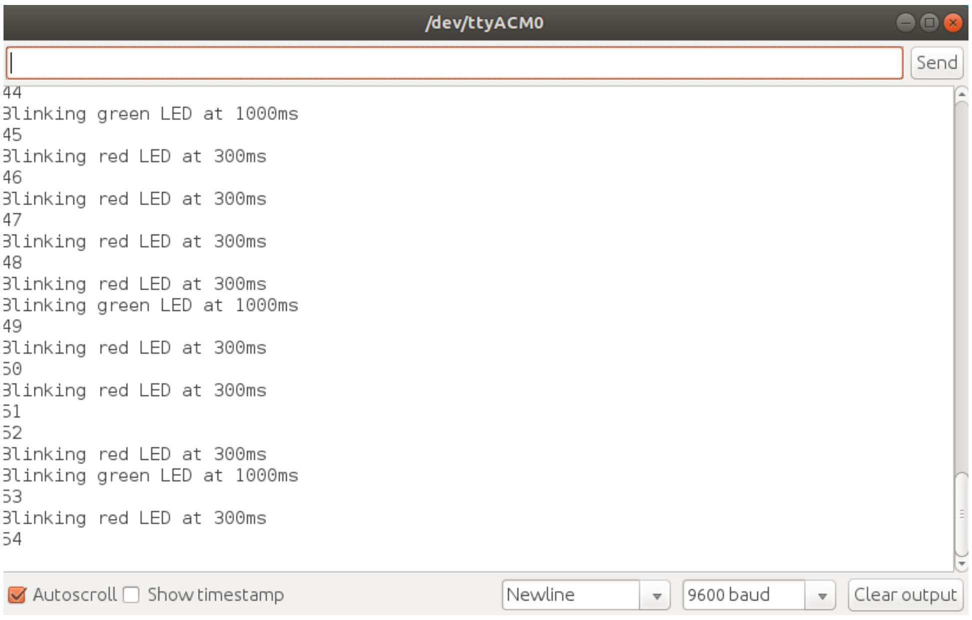
Now, we will implement the required functions as shown below for the first task i.e., LED blink at Digital pin 8 with 200ms frequency.

```
    void TaskBlink1(void *pvParameters) {
    pinMode(8, OUTPUT);
    while(1){
        digitalWrite(8, HIGH);
        vTaskDelay( 200 / portTICK_PERIOD_MS );
        digitalWrite(8, LOW);
        vTaskDelay( 200 / portTICK_PERIOD_MS );
     }
    }
```

Similarly, we can implement second task i.e., LED blink at Digital pin 7 with 300ms frequency. The third task i.e., Print numbers in serial monitor with 500ms frequency will be written as

```
void Taskprint(void *pvParameters)  {
int counter = 0;
while(1){
    counter++;
    Serial.println(counter);
    vTaskDelay( 500 / portTICK_PERIOD_MS );
 }
}
```

Thus, we can now run this code on Arduino Uno to perform three tasks as mentioned above. The code to run these tasks using FreeRTOS is available in a GitHub repository.



```
44
Blinking green LED at 1000ms
45
Blinking red LED at 300ms
46
Blinking red LED at 300ms
47
Blinking red LED at 300ms
48
Blinking red LED at 300ms
Blinking green LED at 1000ms
49
Blinking red LED at 300ms
50
Blinking red LED at 300ms
51
52
Blinking red LED at 300ms
Blinking green LED at 1000ms
53
Blinking red LED at 300ms
54
```

Figure 5.4: Serial Monitor of Arduino IDE with the Tasks (being executed)

The simulation results on the serial monitor of Arduino IDE is as shown in the figure 5.4 and the video of the simulation is available on YouTube. In this video, the red LED and the green LED are blinking with 300ms frequency and 1000ms frequency, respectively. This significant difference in the two frequencies facilitates the clear visualization of two LEDs blinking at different rates.

5.4 RTOS versus Bare-Metal Scheduling

The use of an RTOS or a bare-metal scheduler is a popular topic of debate among embedded system developers. The supporters of bare metal argue that they can use a combination of priority-based interrupts and timers to get RTOS-equivalent behavior with better performance and memory footprint. The RTOS side stresses ease of scheduling and system integration, for starters. We will discuss some of the important reasons why a developer may decide to start with an RTOS over a bare-metal scheduler [27].

- **Concurrency**: Micro-controller based systems typically only have a single processing core but a need to execute multiple tasks. In applications where tasks need to appear to be executing at the same time or concurrently, the use of an RTOS makes sense. An RTOS can have multiple tasks simultaneously in memory and can switch between them based on events and priorities. A bare-metal scheduler could be used, but tasks in a bare-metal system usually execute one at a time and not concurrently.

- **Pre-emption**: Pre-emption is the ability of an operating system to temporarily suspend a task in order to execute a higher-priority task. If the embedded software that is being developed requires the need to prioritize tasks and interrupt tasks that are currently running, an RTOS is the go-to operating system. The nature of most RTOS systems is to determine which tasks should be executing at any given time based on the priority of the task and system conditions. A bare-metal scheduler can be developed that emulates this type of behavior using priority-based interrupts, but the use of an RTOS is more appropriate for the situation.

- **Available RAM**: The amount of available RAM on a micro-controller can be a big determining factor as to whether an RTOS or a bare-metal scheduler is used. Resource-constrained systems that have less than 4 kilobytes of RAM can be difficult to fit within memory due to the fact that each task has its own task control block and stack. A bare-metal system, on the other hand, typically has just the one stack and doesn't require the extra overhead necessary to keep track of the state of each system task. At a minimum, micro-controller-based systems should have at least 4 kilobytes of RAM (preferably 8 kB) before going with an RTOS solution.

- **Available Flash**: Since a developer should look at how much RAM is available on a system before deciding to go with a RTOS, he or she should also look at how much flash space is available. RTOS systems don't take up much flash space, usually on the order of eight to 10 kB, but if the micro-controller only has 16 kB of flash space, there really isn't much room left for the application code. If the micro-controller has at least 32 kB of flash space, then the system is a good candidate for the use of an RTOS. Anything less and it might be time to dust off the bare-metal scheduler or upgrade the hardware.

- **Synchronization Tools**: One of the problems with using a bare-metal scheduler is that it lacks synchronization tools that are included by default in a RTOS. For example, an RTOS has Mutexes that can be used to protect a shared resource, and Semaphores that can be used to signal and synchronize tasks and message queues to transfer data between tasks. Properly designing and implementing these core software features isn't trivial, and adding them into a bare-metal scheduler from scratch will undoubtedly inject bugs. If a system has multiple tasks and protected resources that require synchronization, then the use of an RTOS is the wise decision.

- **Third-Party Software**: One of the problems facing many developers today is how to integrate third-party software stacks and tools into their embedded system. Few developers want to write a TCP/IP or USB stack. Many of the third-party stacks and tools that are available on the market are compatible with various RTOSs. The use of an RTOS makes these components plug-and-play within the software and can drastically accelerate software development. The decision to use third-party software could be a major indicator that an RTOS should be used over a bare-metal scheduler.

- **Ease of Use**: RTOS systems are readily available for nearly every micro-controller and for nearly application imaginable. Whether a developer just wants to create a rapid prototype or build a robust safety-critical system, an RTOS exists that developers can leverage and get up and running fairly quickly. Creating tasks and utilizing RTOS tools is easy and very powerful, but developers need to beware that they properly analyze their tasks and think through their system design. An RTOS is a powerful tool, but improper use can result in tragic results.

Chapter 6

Conclusion

In this report, we discussed the difference between a real-time task and a non-real-time task. We realised that a non-real-time task is not associated with any time bounds. A few examples of non-real-time tasks are: batch processing jobs, e-mail, and back ground tasks such as event loggers. One may however argue that even these tasks, in the strict sense of the term, do have certain time bounds. For example, an e-mail is expected to reach its destination at least within a couple of hours of being sent. Similar is the case with a batch processing job such as pay-slip printing.What then really is the difference between a non-real-time task and a soft real-time task? For non-real-time tasks, the associated time bounds are typically of the order of a few minutes, hours or even days. In contrast, the time bounds associated with soft real-time tasks are at most of the order of a few seconds.

Along with this, we compared the functions of an RTOS and a GPOS. Next, we also discussed the various scheduling techniques which should be exploited to deal with real-time sensing and control systems. At the end, we investigated the available real-time control methodologies using open-source tools like RTLinux, RTAI-Lab, `StateGraph`, FreeRTOS, etc. We also ran a few simulations on OpenModelica and Arduino. It was found that these open-source tools perform well while handling real-time control. However, there is a need to run the simulations on complex systems to check whether the real-time tools discussed are able to meet the hard real-time constraints.

Bibliography

[1] Mainframe vs PC, https://blog.syncsort.com/2018/10/mainframe/mainframes-vs-pc-4-things/

[2] Introduction to Real-Time Systems, https://nptel.ac.in/content/storage2/courses/108105057/Pdf/Lesson-28.pdf

[3] Real-Time Systems, https://users.ece.cmu.edu/~koopman/des_s99/real_time/

[4] Real-Time Systems, https://www.cse.unsw.edu.au/~cs9242/08/lectures/09-realtimex2.pdf

[5] Intro to Real-Time Linux for Embedded Developers, https://www.linuxfoundation.org/blog/2013/03/intro-to-real-time-linux-for-embedded-developers/

[6] Modelica.StateGraph, https://build.openmodelica.org/Documentation/Modelica.StateGraph.html

[7] Difference between Clock-driven and Event-driven Scheduling, https://www.geeksforgeeks.org/difference-between-clock-driven-and-event-driven-scheduling/

[8] Program for Round Robin scheduling, https://www.geeksforgeeks.org/program-round-robin-scheduling-set-1/

[9] S. Han, K. Lam, J. Wang, K. Ramamritham and A. K. Mok, "On Co-Scheduling of Update and Control Transactions in Real-Time Sensing and Control Systems: Algorithms, Analysis, and Performance," in IEEE Transactions on Knowledge and Data Engineering, vol. 25, no. 10, pp. 2325-2342, Oct. 2013, doi: 10.1109/TKDE.2012.173.

[10] P. Marti, J. M. Fuertes, G. Fohler and K. Ramamritham, "Improving quality-of-control using flexible timing constraints: metric and scheduling," 23rd IEEE Real-Time Systems Symposium, 2002. RTSS 2002., Austin, Texas, USA, 2002, pp. 91-100, doi: 10.1109/REAL.2002.1181565.

[11] RTOS Fundamentals, https://www.freertos.org/implementation/a00002.html

[12] Ramamritham, K. (1999, December). Can real-time systems be built from off-the-shelf components?. In Proceedings Sixth International Conference on Real-Time Computing Systems and Applications. RTCSA'99 (Cat. No. PR00306) (pp. 226-226). IEEE.

[13] Real-time operating system (RTOS): Components, Types, Examples, https://www.guru99.com/real-time-operating-system.html

[14] Scilab, Open source software for numerical computation, https://www.scilab.org/

[15] OpenModelica, Open-source Modelica-based modeling and simulation environment intended for industrial and academic usage, https://openmodelica.org/

[16] Arduino, Open-source electronics platform based on easy-to-use hardware and software, https://www.arduino.cc/

[17] Real-Time Linux, https://www.embedded.com/real-time-linux/

[18] RTAI - Wikipedia, https://en.wikipedia.org/wiki/RTAI

[19] Arm, J., Bradac, Z., & Kaczmarczyk, V. (2016). Real-time capabilities of Linux RTAI. IFAC-PapersOnLine, 49(25), 401-406.

[20] Adaptive Domain Environment for Operating Systems - Wikipedia https://en.wikipedia.org/wiki/Adaptive_Domain_Environment_for_Operating_Systems

[21] RTAI: Real-Time Application Interface, https://www.linuxjournal.com/article/3838

[22] C. Meza, J. A. Andrade-Romero, R. Bucher and S. Balemi, "Free open source software in control engineering education: A case study in the analysis and control design of a rotary inverted pendulum," 2009 IEEE Conference on Emerging Technologies & Factory Automation, Mallorca, 2009, pp. 1-8, doi: 10.1109/ETFA.2009.5347162.

[23] Peter Fritzson, Principles of Object-Oriented Modeling and Simulation with Modelica 3.3: A Cyber-Physical Approach, ISBN: 978-1-118-85912-4, April 2015, Wiley-IEEE Press.

[24] Hardware-in-the-loop simulation - Wikipedia, https://en.wikipedia.org/wiki/Hardware-in-the-loop_simulation

[25] OpenModelica (C-runtime) Simulation Flags, https://www.openmodelica.org/doc/OpenModelicaUsersGuide/latest/simulationflags.html

[26] Arduino FreeRTOS Tutorial, https://circuitdigest.com/microcontroller-projects/arduino-freertos-tutorial1-creating-freertos-task-to-blink-led-in-arduino-uno

[27] Do You Need an RTOS?, https://www.designnews.com/electronics-test/do-you-need-rtos-yes-and-here-are-7-reasons-why/29593780546421