RTFrame: An Object-Oriented Application Framework for Real-Time Applications

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Abstract

Real-time systems and applications impose stringent timing constraints on critical tasks. The design of such systems are more complex than that of conventional systems, because correctness and performance, besides being key system design issues, are directly related to system feasiblility. Object-oriented application frameworks have been proposed for communication systems, distributed applications, medical imaging, and financial engineering. On the contrary, there has been relatively little work on an application framework for the design of a general real-time system. Facing the growing need for such systems, we propose a novel framework, called RTFrame, especially for real-time systems. RTFrame consists of five components: Specifier, Extractor, Scheduler, Allocator, and Generator. Within RTFrame, several design patterns have been proposed for real-time systems. Experiences of using RTFrame show a significant increase in design productivity through design reuse, and a significant decrease in design time and effort.

1: Introduction

Real-time systems such as telecommunications, avionics, multimedia, robotics, factory automation, etc. impose timing constraints on executing tasks. Violation of such constraints usually result in an incorrect system. Hence, appropriate task scheduling and resource allocation become a crucial part of all real-time systems design. It is here that object-oriented application frameworks can be taken advantage of for reusing classes and design strategies. Corresponding to different specification styles and scheduling policies, different design patterns can be proposed. Combining design patterns and components, a novel object-oriented application framework called RTFrame is proposed for the design of real-time systems. RTFrame helps designers of real-time systems increase productivity, decrease design time and effort, enhance manageability, and increase design reuse.

A *real-time system* is generally specified as a collection of *tasks* which might share resources. The tasks are usually independent and periodic. Execution time, period, deadline, type of priority and resource requirements are specified for each task. Hard real-time systems do not allow the violation of any timing constraint, that is, no task must violate its deadline. Soft real-time systems strive to minimize deadline violations. To statically guarantee satisfaction of all timing constraints, the tasks must be scheduled using *priority-based* scheduling algorithms such as rate-monotonic (RM) [15], earliest-dealine first (EDF) [15], mixed-priority (MP) [15], pin-wheel, etc. or using *timed-based* scheduling algorithms. Dynamic monitoring of timing constraints in distributed real-time systems can also be achieved by taking into account the drift among various processor clocks [10].

Object-oriented (OO) technology employs *encapsulation* and *inheritance* as basic reuse techniques. Objects are identified in a system, encapsulated, and positioned in a hierarchy of classes, by taking into account their inter-relationships. *Class libraries* are thus the basic structures for reusing objects. System designers found such libraries to be limited in their reuse capability due to their generality. The libraries strived to cater a more general purpose reuse. Recently, several application-domain techniques have been proposed, which significantly improve the degree of reuse. Design patterns, software architectures, components, and object-oriented application frameworks are widely used reuse techniques, ordered in the ascending order of their degrees of reuse.

Design pattern is a problem-solution pair that captures successful development strategy. Patterns aid in reusing successful design strategies by giving a more abstract view to concrete design strategies. For example, some core design patterns are Adaptor, Proxy, Facade, and Bridge [5]. Components are self-contained instances of abstract data types that can be integrated into complete applications. Examples include VBX Controls and CORBA Object Services. A component acts as a black-box allowing designers to reuse it through knowledge of its interface only.

An object-oriented application framework (OOAF) is a reusable, "semi-complete" application that can be specialized to produce custom applications [11]. OOAF are application-domain specific reuse methods, such as user interfaces or real-time avionics. Examples include MacApp, ET++, Interviews, ACE, Microsoft's MFC and DCOM, Javasoft's RMI and implementation of OMG's CORBA. Frameworks can be further distinguished by their scope into *system infrastructure frameworks* (used internally within a software organization), *middleware integration frameworks* (used to integrate distributed applications and components), and *enterprise application frameworks* (used in application-specific domains) [4].

Object-oriented technology has been used in the development of real-time systems for quite some time now. Research literatures have shown how the concept of objects in real-time systems can be useful. Object-oriented real-time (OORT) system models such as MO2 [1], evaluation taxonomy such as in [8], object-oriented real-time language design [9], concurrency exploitation in OORT systems using metrics-driven approach [21], checking time constraints [6], and verification of function and performance for OORT systems [3] are some of the recent work on applying OO technology to real-time system design.

Although object-oriented technology has been applied to the design of real-time systems in several proposed work, but there has been little work on the development of an OOAF for real-time system application design, except for a single one called *Object-Oriented Real-Time System Framework* (OORTSF) [13]. OORTSF is a simple framework and only lists the classes used in real-time application development. No design patterns have been proposed specific to real-time system application design. This results in a difficult comprehension of the collaboration among the classes. It is also very difficult to design a system using OORTSF if the design patterns are unclear. The flexibility of specifying real-time objects, the ease of using OORTSF, the benefits of applying OORTSF, and other issues related to OOAFs are unclear from the work. According to the knowledge of the author, besides OORTSF, there is no other work on *enterprise application frameworks* devoted to real-time system application development. As far as *middleware integration frameworks* are concerned, there has been a TAO Real-Time Object Request Broker (ORB) proposed by Schmidt [19].

The rest of this paper is organized as follows. Section 2 gives two views of our RTFrame framework, namely *Components-Patterns view* and *Class view*. All the design patterns and components used are also described in this section. Section 3 illustrates how a designer may use RTFrame to actually develop a real-time system. Section 4 is the final conclusion.

2: RTFrame framework

For ease of comprehension, we present two different views of our RTFrame framework: a *Components-Patterns View* and a *Class View*. The components-patterns view allows a designer to better understand *how* exactly must RTFrame be used and the class view allows him/her to grasp *what* exactly are the classes to be used. Our presentation is thus based on two complementary levels of description: an *abstract* components-patterns view and a *concrete* class view.

2.1: Components-patterns view of RTFrame

This view is illustrated in Fig. 1. The notation used in this paper is based on that proposed in Rumbaugh's Object Modeling Technique (OMT) [18]. The order of the RTFrame components used by a designer to design a system is: Specifier, Extractor, Scheduler, Allocator, and Generator. Application domain objects are specified using the Specifier. Real-time constraints are either specified separately or coupled with the application domain objects. In the latter case, Extractor is used for extracting constraints. Extractor is also used to extract tasks from the given domain objects. Scheduler schedules the tasks using some scheduling algorithm and Allocator allocates resources among the tasks that are running concurrently. Finally, Generator is used to generate the application code based on the decisions made in the other components.

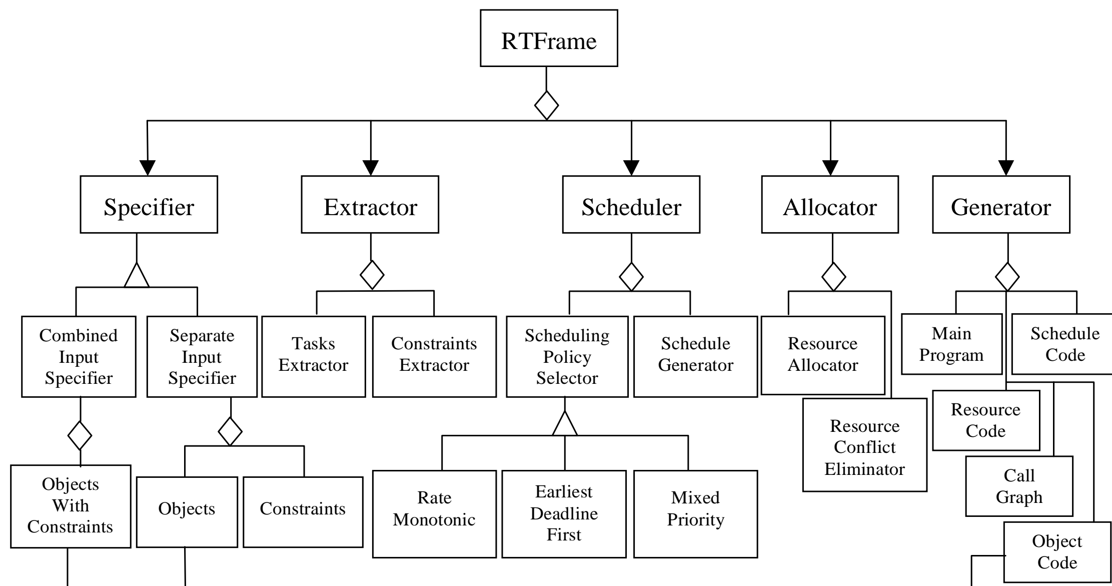

Figure 1. Components-Patterns View of RTFrame

2.1.1: Specifier

This component is the main interface between application domain objects and RTFrame. *Application domain objects* are those objects that constitute the application that the designer desires to design. Three design patterns are used in this component: *Objects-with-Constraints*, *Objects-without-Constraints*, and *Tasks-with-Constraints*. We call them design patterns because often the

real-world objects are not specified as tasks, whereas a real-time system application is generally described in terms of a set of canonical tasks. This semantic gap has become a design issue [6] and topic of research for the object-oriented model of real-time systems. The three design-patterns correspond to how RTFrame provides the designer with the flexibility of choosing either (1) to specify application domain *objects* with constraints *coupled* to the objects, or (2) to specify application domain *objects* with constraints as a *separate* entity, or (3) to specify real-time *tasks* with constraints. The first two design patterns do not explicitly specify what the tasks are. This specification is left to RTFrame and RTFrame accomplishes it using Extractor as will be described in the next subsubsection. Timing constraints coupled to the objects are specified as *annotations* to methods [6]. The specification language could be C++ with annotations [6], a real-time extension of C++ called RTC++ [9], ARTS/C and ARTS/C++ used in the ARTS real-time distributed operating system kernel [20], real-time Euclid [12], real-time Mentat [7], or FLEX [14]. Currently, only C++ with annotations is supported in RTFrame. Future implementations will include RTC++.

2.1.2: Extractor

This component transforms the specification provided by the designer within Specifier into a uniform intermediate format suitable for schedulability analysis. The intermediate format is necessary since Specifier allows the designer several choices of specifying his/her application. The main job of Extractor is to extract important information from the objects and formulate them into two parts: a Task-Table object and a Call-Graph object. All task-related information are instantiated into a Task-Table object for future reference. This object consists of the task index, the method name, its execution time, period, deadline, type of priority (fixed or dynamic), and its resource requirements. The resource requirement is specified as an real-numbered vector, where each element corresponds to some system resource such as memory, processor utilization, ... and the real-number corresponds to the amount of each resource required by the particular task. System resources are specified by the designer within Specifier through instantiation of application domain objects. Extractor also generates a Call-Graph object which is a directed graph $G = (V, E)$, nodes in V represent tasks and arcs in E represent the call relationships between two tasks. This graph is useful for schedulability test, resource allocation, scheduling, and conflict resolution.

2.1.3: Scheduler

The Call-Graph and the Task-Table objects instantiated in Extractor is scheduled into a feasible application by Scheduler. As described in Section 1, there are many priority-based scheduling policies such as rate-monotonic, earliest-deadline first, mixed priority, pin-wheel, et al. It is sometimes evident from the application, as to which scheduling policy should be applied. But, in most applications, the prime concern is the satisfaction of the timing constraints, irrespective of which scheduling algorithm is applied. Scheduler includes a design pattern similar to the *Strategy Pattern* [5] adapted to real-time systems.

This component mainly consists of two parts: a *Policy Selector* (PS) and a *Schedule Generator* (SG). The designer can choose to assign a particular scheduling policy he deems fit or the designer can also choose to allow RTFrame determine automatically the right choice. The choice is made by performing schedulability tests with respect to each scheduling algorithm. One of the scheduling algorithms in the successful cases is then selected as the automatic decision result. This selection can be arbitrary or based on some criteria such as the shortest schedule length (i.e., the shortest scheduled time). Currently, RTFrame leaves this option to the designer. Schedule Generator generates the actual start/end timing of each task based on the schedule policy chosen and on the Call-Graph constraints such as precedence relationships.

2.1.4: Allocator

Resource allocation is handled by this component, which is composed of two modules: a Resource Allocator and a Conflict Eliminator. The scheduled Call-Graph does not yet contain any resource information. It is in this component that resources are allocated to each task based on its resource requirements recorded in the Task-Table. It may happen that certain tasks, scheduled to be simultaneously executing, conflict in their resource requirements. The last arriving task (i.e., the task with the latest starting phase) is delayed and rescheduled. If more than one conflicting tasks start at the same time, then the task that has a smaller requirement of the conflicting resources is delayed for rescheduling. If no partial order can be assigned to the resource requirements of two or more conflicting tasks then an arbitrary choice of task is made for delay and rescheduling. Conflicts in resource requirements of scheduled tasks are thus eliminated and the resulting scheduled Call-Graph is a feasible one for code generation.

2.1.5: Generator

The final component of RTFrame is responsible for generating the OO code for the real-time application under development by the designer. It consists of mainly five parts: the main OO program, the schedule code, the resource allocation code, the tasks Call-Graph code and the user-given domain object code. The code hierarchy is a *calling* hierarchy, that is, the main OO program calls schedule code functions and the resource allocation code functions, which in turn call the call-graph code methods, and finally the user-given object code is called for execution. Two auxiliary codes used for reference are Resource-Table and Task-Table, which contain all the information for system resources and tasks.

The main OO program maintains a global clock which is used for recording progress in the developed system or application. It also contains exception handles to error recovery, fault handling, and other mechanisms to handle exceptions such as constraint violations. The main program ensures that the system is always in an acceptable state. This is achieved by calling the schedule code functions and resource handling functions in the resource allocation code.

The schedule code is an implementation of the actual scheduling of the tasks in the Call-Graph and after any resource conflicts are eliminated. This code depends on the scheduling policy selected either by the user or by RTFrame. The schedule code consists of the actual time a task must start execution and the time it should terminate. Everything is settled statically for optimal performance and satisfaction of timing constraints in real-time systems.

Resources related information are all recorded in the Resource-Table object. Resource allocation code is responsible for accepting resource allocation/deallocation requests, transmitting them to the resource codes (or the actual physical resources in case of a hardware real-time system), handling exceptional situations such as dynamic resource failure and recovery, and resource conflict handling. Although resource conflicts among tasks were eliminated statically in the scheduled Call-Graph (refer to the Allocator component of RTFrame), yet conflicts may still arise in exceptional situations when resources become faulty, when tasks violate timing constraints due to external environmental disruptions, ...

The Call-Graph code is an implementation of the resource-allocated, scheduled Call-Graph object. This code is required in spite of the calling scheme of tasks (method calls) being implicit in the user-given domain object code, because scheduling information and resource requests are, respectively, not given and not explicit in the object code. The object code is just the user-given code. The hierarchical structure of the code generated by RTFrame has many advantages including easy debugging, code modularization, and explicit interface with user-given code.

2.2: Class view of RTFrame

Having an overview of how RTFrame goes about developing an application, a designer must now actually deal with the classes provided by RTFrame to craft his/her application. Figure 2 shows the hierarchy of classes provided by RTFrame. The notation used is Object Modeling Technique (OMT) [18]. Pertaining to real-time systems, the classes can be classified into three parts: Application Objects, Scheduling Policy, and Resource Manager. There is also a Global-Clock class which is responsible for maintaining the global timing of the system. The designer can instantiate any class in the hierarchy by filling in the data attributes and the member function definitions. When information is partially entered, requests for more data values or function definitions will be made by RTFrame after an overall analysis.

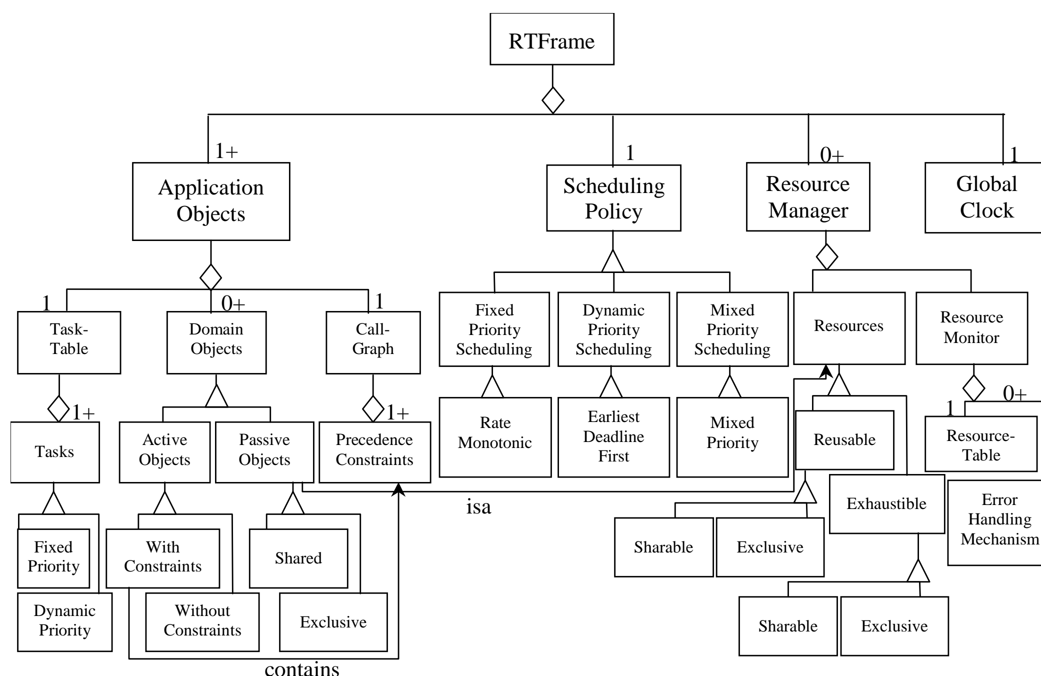

Figure 2. Class View of RTFrame

2.2.1: Application objects

A designer can choose to either instantiate the application objects by specifying domain objects (real-world objects concerned with the application) or by specifying a more abstract but useful view of the application through two classes: Task-Table and Call-Graph. When specification is made in the form of domain objects, Extractor component (as explained in Section 2.1.2) instantiates Task-Table and Call-Graph classes.

The Task-Table class is composed of one or more Task class(es), each of which consists of data attributes such as the computation time of each instance of a task (called a *job*), the period of execution, the deadline for a job (this is usually the same as its period, but could also be a multiple), the phase (this is normally assigned values after scheduling and resource conflict elimination), and the resource requirements (this is a vector specifying how much of each resource is required). Task

class also consists of member functions such as task-setup(), task-execution(), task-start(), task-end(), request-resource(), and deadline-violation-handler().

Call-Graph class is defined as a separate class so as to partition the task objects and their call relationships. This class mainly consists of data attributes such as precedence constraints (the predecessors and the successors of each task) and delay constraints (the time delay between two tasks). The member functions include context-switch(), context-delay(), and switch-error-handler().

The domain objects are defined by the designer, if necessary. Domain objects are classified into two types: *active* and *passive*. Here, *an active object* accesses and changes the state of some other object, whereas *a passive object* is one whose state is accessed and changed by some other object. For example, a system controller is an active object, whereas a database or memory record is a passive one. This classification is necessary for identifying system resources. Access of system resources is critical to system correctness. The active objects can be instantiated in two ways: *with* and *without* constraints. In the case of without constraints, the designer must instantiate Task-Table class at the same time to specify the task constraints. Constraints can also be specified inside the objects as method annotations [6]. Currently, only C++ annotations are supported. Future work will include RTC++ and other real-time language constructs for constraints specification.

2.2.2: Scheduling-Policy

Scheduling-Policy is responsible for providing the scheduling code for the scheduled tasks. Priority-based scheduling policies are supported in RTFrame. There are three kinds of priorities: fixed (statically assigned), dynamic (changes during execution), and mixed (some tasks are fixed and some are dynamic). For fixed priority-based scheduling, the popular rate-monotonic scheduling algorithm is supported. For dynamic priority-based scheduling, the earliest deadline first scheduling algorithm is supported. For mixed priority, the scheduling algorithm given in [15] is supported. The data attributes of the Scheduling-Policy class include priority type, scheduling algorithm and scheduling mode (automatic or user-specified). Member functions include assign-task-start-time() and assign-task-end-time().

2.2.3: Resource-Manager

Resources are passive objects which are accessed and modified by other objects. Resource-Manager keeps a record of all such passive objects in the Resource-Table class. Each resource object has data attributes including use-type (exhaustible or reusable), share-type (sharable or exclusive use), value (it may be a simple integer or a complex record), and status (currently in use, free, or allocated). Member functions of a resource object include grant-resource(), free-resource(), read-value(), change-value(), get-status(), and conflict-handler().

2.2.4: Global-Clock

This special class maintains the system time. The temporal increment can be changed by the designer as required. The initial value of Global-Clock is zero and it increments at a uniform rate. The data attributes include value (the time of the system), initial value, breakpoint value, and final value. Member functions include start-timer(), stop-timer(), reset-timer(), record-breakpoint-value(), change-increment(), and read-value().

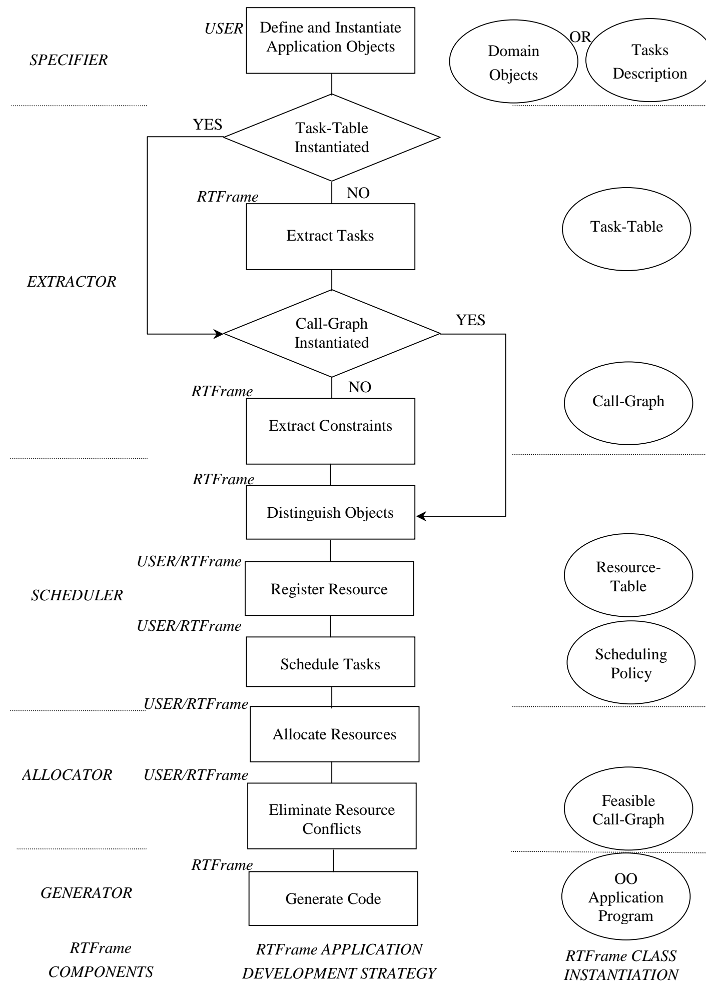

Figure 3. Application Development using RTFrame

3: Application development

The previous section has given an overview of the RTFrame framework from two different perspectives: the Components-Patterns view and the Class view. This section will describe how actually can a designer design a real-time application using RTFrame. Figure 3 illustrates the development strategy in context with both the Components-Patterns view and the Class view of RTFrame. Rectangular boxes represent processes to be accomplished either by the user (i.e., the designer) or the RTFrame framework. Diamonds represent a yes/no question. Ovals represent classes.

A user of RTFrame (also called the designer) begins with specifying his/her system. Either application domain objects may be defined or tasks directly input by instantiating the Task-Table class and the Call-Graph class. When application domain objects are specified, Task-Table and Call-Graph are instantiated by RTFrame through the Extractor component. An example of real-time applications has been developed using RTFrame. It is described in the rest of this section.

An illustrative example is an avionics system application: digital flight control [2]. The 24 tasks in this example are specified as shown in Table 1 [17, 2, 16]. The hardware resource for executing

Table 1. Avionics Example: Digital Flight Control Tasks [2]

Index	Task Description	Run Time (ms)	Period (ms)	Utilization	Memory
1	Attitude Control	2.456	50.00	0.04912	2,075
2	Flutter Control	0.276	4.00	0.06900	92
3	Gust Control	0.116	4.17	0.02784	60
4	Autoland	0.684	6.25	0.10944	1,025
5	Autopilot	0.400	200.00	0.00200	250
6	Attitude Director	5.120	33.33	0.15360	1,310
7	Inertial Navigation	2.700	40.00	0.06750	2,250
8	VOR/DME	1.540	200.00	0.00700	300
9	Omega	1.600	200.00	0.00800	505
10	Air Data	0.400	200.00	0.00200	135
11	Signal Processing	3.500	5000.00	0.00070	315
12	Flight Data	11.040	200.00	0.05520	550
13	Airspeed	1.098	62.50	0.01757	430
14	Graphics Display	7.950	125.00	0.06360	6,250
15	Text Display	3.800	100.00	0.03800	9,340
16	Collision Avoidance	0.064	1.49	0.04288	1,150
17	Onboard Communication	0.056	4.00	0.01400	705
18	Offboard Communication	0.310	250.00	0.00124	687
19	Data Integration	0.720	250.00	0.00288	1,300
20	Instrumentation	5.584	200.00	0.02792	1,900
21	System Management	4.640	2000.00	0.00232	950
22	Life Support	4.640	2000.00	0.00232	950
23	Engine Control	7.194	30.30	0.23740	1,500
24	Executive	0.400	200.00	0.00200	1,100

these tasks is the SIFT (Software-Implemented Fault-Tolerance) computer [17]. We consider 8 processors, with each processor having an instruction execution rate of 0.5 MIPS and an address space of 64 Kbytes. Since the total utilization [2] of each task does not exceed the rate-monotonic scheduling upper bound of 0.693 [15], rate-monotonic scheduling is used. This application when developed with RTFrame took only one week for a real-time system designer. The same designer took approximately five weeks to design the same application. This is because a lot of things need only be specified into RTFrame without caring for the details such as how tasks are scheduled, how resources are allocated, etc.

4: Conclusion

An object-oriented application framework, called RTFrame, was proposed for real-time systems application development. The presentation included two different perspectives of RTFrame: a Components-Patterns view and a Class view. Several design patterns related to real-time system design were proposed and implemented in RTFrame. Besides reuse, RTFrame also automates several design phases of real-time system application development, including tasks extraction, constraints extraction, scheduling, and resource allocation. All of these design phases were very pain-staking and laborious originally when a designer had to develop either from scratch or using different specialized tools such as scheduling analysis tool, allocation tool, etc.

RTFrame can be easily extended since new specification languages, scheduling algorithms, etc.

can always and easily be integrated into it. Future extensions will include RTC++ support and other scheduling algorithms. More examples will also be developed using RTFrame.

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