GNAT Pro for On-Board Mission-Critical Space Applications *

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Abstract. This paper describes the design and implementation of GNAT Pro for ERC32, a flexible cross-development environment supporting the Ravenscar tasking model on top of bare ERC32 computers. The static and simple tasking model defined by the Ravenscar profile allows for a streamlined implementation of the run-time system directly on top of bare machines. The reduced size and complexity of the run time, together with its configurability, makes it suitable for mission-critical space applications in which certification or reduced footprint is needed. Software reliability and predictability is also increased by excluding non-deterministic and non analysable tasking features. Product validation has been achieved by means of a comprehensive test suite intended to check compliance with the Ravenscar profile and Ada standards, and correct behaviour of specialised features and supplemental tools. Code coverage analysis is also part of the validation campaign, with the goal of achieving 100% statement coverage.

1 Introduction

The Ada tasking model allows the use of high level abstract development methods that include concurrency as a means of decoupling application activities, and hence making software easier to design and test [23]. However, tasking capabilities have been considered as too complex for safety critical systems because accurate timing analysis is difficult to achieve. Advances in real-time systems timing analysis methods have paved the way to reliable tasking in Ada. The Ravenscar profile is a subset of Ada 95 tasking that provides the basis for the implementation of deterministic and time analysable applications on top of a streamlined run-time system.

This paper describes the design and implementation of a flexible cross-development system supporting the Ravenscar tasking model on top of bare ERC32 computers. ERC32 [13, 4] is a highly integrated, high-performance 32-bit RISC embedded processor implementing the SPARC architecture V7 specification. It has been developed with the support of the European Space Agency (ESA) as the current standard processor for spacecraft on-board computer systems.

In addition to a large number of compiler features intended to detect violations of the Ravenscar profile limitations (and any other imposed restrictions) at compile time,

* This work has been funded by ESA/ESTEC contract No.17360/03/NL/JA and carried out in cooperation between AdaCore and the Technical University of Madrid.

the key element is the provision of a restricted Ada run time that takes full advantage of the Ravenscar profile restrictions [3]. Additional restrictions on the Ada subset to be used can be enforced in order to properly support the development of high integrity systems [17]. The purpose of such restrictions is to enable a wide range of static analysis techniques, including schedulability analysis, to be performed on the software for validation purposes.

The developed Ada run time takes full advantage of the largely enhanced modularity introduced in GNAT Pro recently. Key to achieving this goal is the fully configurable and customisable run-time library, which allows for limiting the run-time library just to those units required for the application.

The cross-development environment provides a full-featured visual programming environment that covers the whole development cycle (language-oriented editing, compiling, binding, linking, loading, graphical tasking-aware debugging).

The work described is this paper builds on some of the results of previous ESA projects which resulted in the development of UPM's *Open Ravenscar Kernel* (ORK) [9, 25], an open-source development aimed at demonstrating the feasibility of a Ravenscar-compliant Ada run time on top of a bare ERC32.

2 The Ravenscar profile

The Ravenscar profile [7, 3, 2] defines a subset of the tasking features of Ada which is amenable to static analysis for high integrity system certification, and that can be supported by a small, reliable run-time system. This profile is founded on state-of-the-art, deterministic concurrency constructs that are adequate for constructing most types of real-time software [8]. Major benefits of this model are:

- Improved memory and execution time efficiency, by removing high overhead or complex features.
- Increased reliability and predictability, by removing non-deterministic and non analysable features.
- Reduced certification cost by removing complex features of the language, thus simplifying the generation of proof of predictability, reliability, and safety.

The tasking model defined by the profile includes a fixed set of library level tasks and protected types and objects, a maximum of one protected entry per protected object with a simple boolean barrier and no entry queues for synchronisation, a real-time clock, absolute delays, deterministic fixed-priority preemptive scheduling with ceiling locking access to protected objects, and protected procedure interrupt handlers, as well as some other features. Other features, such as dynamic tasks and protected objects, task entries, dynamic priorities, select statements, asynchronous transfer of control, relative delays, or calendar clock, are forbidden.

The compiler and run time have been developed to be fully compliant with the latest definition of the Ravenscar profile [3, 2], so that it will be compliant with the forthcoming ISO standard revision of the Ada language.

3 The high integrity approach

The high integrity edition of the GNAT Pro compiler is intended to reduce costs and risks in developing and certifying systems that have to meet safety standards, such as DO-178B [12], DEF Stan 00-55 [10], and IEC 61508 [15].

The centerpiece of this approach is the "configurable run time" capability. Application developers and system integrators can together define an Ada subset that closely fits the needs of the projects, thus limiting the cost of certification of the run time. Run-time subsets are defined by using three different mechanisms:

- Setting parameters in the *System* package.
- Including only a subset of available run-time system units.
- Using *pragma Restrictions*.

The compiler will then flag and reject the use of constructs that are not supported by the defined subset. Developers may use presupplied implementations of units of interest, or may develop their own alternatives. This approach gives great control over the scope of certification activities when developing in Ada.

While the configurable run time approach gives maximum flexibility, in many situations a project does not require such a level of customisation. The ERC32 toolchain therefore includes three specific instantiations of the configurable run-time library:

- The *Zero FootPrint* run time guarantees that the generated object modules contain no references to the GNAT Pro run-time library. This allows the construction of a standalone program that has no code other than that corresponding to the original source code (apart from the elaboration routine generated by the binder). The elaboration routine generated by the binder also avoids any reference to run-time routines or data. This run time is designed to reduce the cost of meeting safety certification standards for applications written in Ada. In addition, this profile is compatible with SPARK [6].
- The *high integrity Ravenscar* run time offers a multitasking programming environment (compliant with the Ravenscar profile) with maximum performances at the expense of stringent restrictions. This profile is targeted at applications aiming at certification for safety-critical use or very small footprints.
- The *extended Ravenscar* run time offers support for a larger subset of Ada 95, under the restrictions of the Ravenscar profile and the hardware constraints. This profile makes software development easier (debugging, text output, stack checking, etc.), at the expenses of a larger footprint and an increased complexity in the run time.

Although limited in terms of dynamic Ada semantics, these three high integrity profiles fully support static Ada constructs such as generic templates and child units, tagged types (at library level), and other object-oriented programming features. Users can also further restrict certain Ada features (such as dynamic dispatching, allocators, unconstrained objects, implicit conditionals and loops) through appropriate *pragma Restrictions*.

Traceability from Ada source code to object code is facilitated by giving access to different intermediate formats internally generated by the compiler. From the initial

source code the compiler generates a simplified code, which is low level Ada pseudo-code (target independent) that expands complex constructs into a sequence of simpler data and code (including run-time calls). This code is then compiled into assembler code, which is later transformed into object code. The availability of these intermediate representations helps certification of object code by reducing the semantic gap between different representations. Additionally, representation information for declared types and objects is also accessible.

Full Safety and Security Annex support [1, H] is provided, including capabilities for detecting uninitialised variables [11], by means of compiler warnings and run-time errors (using *pragma Normalize_Scalars* and some additional validity checking levels that can be selected by the users).

4 Restricted Ravenscar run time

The run-time system is made up by several libraries that implement functionalities required by features not otherwise generated directly by the compiler. The complexity of the run time basically depends on the features supported.

A compact and efficient run time has been designed to take full advantage of the Ravenscar Profile restrictions, which is substantially different from the run time used when no such restrictions are in effect. The Ravenscar run time provides simplified, more efficient versions for the set of tasking and synchronisation operations.

The Ravenscar run time has been carefully designed to isolate target dependencies by means of a layered architecture. There is a target independent layer, called GNU Ada Run-Time Library (GNARL), which provides the interface that is known by the compiler. The part of the run time that depends on the particular machine and operating system is known as GNU Low-Level Library (GNULL), which provides a target independent interface. GNULL is some glue code that translates this generic interface into calls to the operating system interface, thus facilitating portability. On bare board targets (such as the ERC32 one), GNULL is a full implementation of this interface.

Hence, retargeting the run time to a different operating system is a matter of mapping the GNULL interface (roughly a dozen primitives for creating threads, suspending them, etc.) into the equivalent operations provided by the operating system. Retargeting the run time to a different bare board system requires reimplementing the GNULL layer on top of the Board Support Package (BSP).

4.1 Static tasking model

The implementation takes full advantage of the static Ravenscar tasking model, in which only library level non-terminating tasks are allowed.

First, the complete set of tasks and associated parameters (such as their stack sizes) are identified and defined at compile time, so that the required data structures (task descriptors and stacks) can be statically created by the compiler as global data. Hence, memory requirements can be determined at link time (linking will fail if available memory is not enough) and there is no need for using dynamic memory at run time.

In addition, task creation and activation is very simple and deterministic: the environment task (as part of its elaboration) creates all the tasks in the system, and once that is done all tasks are then activated and executed concurrently, being scheduled according to their priority.

Finally, only library level non-terminating tasks are allowed, so that there is no need for code for completing or finalising tasks, and no support is needed for *masters* and *waiting for dependent tasks* either.

4.2 Simple protected object operations

Protected object operations can be easily implemented taking advantage of the restrictions imposed by the Ravenscar profile:

- No asynchronous operations. There are no abort statements and no timed or conditional entry calls.
- Simple creation and finalisation of protected objects. Protected objects are only allowed at library level, and allocators are not allowed for protected types or types containing protected type components.
- Simple management of entry queues. Only one entry is allowed per protected object, with at most one task waiting on a closed entry barrier. In addition, requeues are not allowed.
- Simple priority handling. Dynamic priorities are not allowed.
- Simple locking operations. On a single processor implementation (such as the ERC32), the ceiling priority rules and the strictly preemptive priority scheduling policy guarantee that protected objects are always available when any task tries to use them [16, 19] (otherwise there would be another task executing at a higher priority), and hence entering/exiting to/from the protected object can simply be done by just increasing/decreasing task's priorities.

Operations related to protected objects without entries are implemented in an even simpler manner because there is no need to check whether there is any task waiting, no need to reevaluate barriers, no need to service entry queues, etc.

In addition, efficient execution of queued protected entries is achieved by implementing what is called the proxy model [14] for protected entry execution. At the end of the execution of any protected procedure (that may change the state of the barriers), if there is a task waiting on the protected object's entry, then the barrier is evaluated, and if needed, the entry is executed by the task that opened the barrier on behalf of the queued task. It enhances efficiency by avoiding unnecessary context switches.

4.3 Exception support

The Ravenscar profile does not place any explicit limit on the features of sequential Ada, and therefore it does not restrict the use of exceptions (in fact, some exception support is required by the Ravenscar profile [18]). Therefore, several schemes are defined for supporting exceptions, providing different levels of functionality and complexity.

The simplest exception scheme supported by the GNAT Pro run time is the "No Exceptions" one, that is called the "exclusion strategy" in [17]. Raise statements and exception handlers are not allowed, and no language-defined run-time checks are generated. Hence, program will become erroneous if a run-time exception does occur, so that the absence of erroneous states usually leading to the raising of an exception must be demonstrated.

The second choice corresponds to the "No Exception Handlers" mechanism (called "belt-and-braces" strategy in [17]). It seeks to avoid dependency on the exception mechanism, but recognises that a predefined exception may nevertheless occur for some unforeseen reason. Exception propagation is not allowed, but exception declarations and raise statements are still permitted. No handlers are permitted; a user-defined last chance exception handler (which cannot resume task execution) is introduced at the outermost scope level, and hence no run-time support is needed. If run-time checking is enabled, then it is possible for the predefined exceptions Constraint_Error, Program_Error, or Storage_Error to be raised at run time.

A third exception handling mechanism is implemented in the *extended Ravenscar Profile*, supporting the full semantics of Ada 83 exceptions; Ada 95 enhancements are not included. This run-time system supports propagation of exceptions and handlers for multiple tasks. The run-time library provided by this profile supports also limited Ada 95 exception occurrences, and Ada.Exceptions.Exception_Name. Mapping of the usual traps for hardware exceptions to Ada exceptions is also done.

The implementation of a forth alternative exception handling mechanism is being considered, supporting the "containment" strategy defined in [17], that would authorise exception handling close to the raising location. When an exception is raised, the exception handler is executed if it is located in any of the enclosing syntactic scopes up to the inner-most subprogram scope. In other words, exceptions are never propagated outside the subprogram where they were raised. Every exception not being handled within its inner-most subprogram scope forces the execution of the last chance handler. No run-time support is needed for exception propagation, so that there is no drawback either in efficiency nor in complexity of the run time.

5 Multitasking core

The Ravenscar profile is designed to be easily supported with a small run time. Within the framework of this project we have also designed and implemented a simple Ravenscar compliant multitasking core that is in charge of task scheduling, dispatching, and synchronisation, interrupt management, and timing services (time-keeping and delays). It implements a preemptive priority scheduling policy with ceiling locking and 256 priority levels (although this number can be easily reconfigured).

It has been written in Ada (except for some low-level code written in assembler to implement context switches and trap handling). A reduced, simple, and safe subset of Ada, following the recommendations made by the ISO 15942 technical report [17], has been used.

In order to enhance portability, it has been designed a Board Support Package (BSP) layer, giving access to key hardware dependent services, that minimises and isolates

specific machine dependencies. It is made up by a few assembly files and a limited and identified set of Ada packages.

5.1 Timing services

The implementation of timing services is both accurate and efficient, providing low granularity (limited only by the oscillator) time measurements and delays together with a low overhead operation, by means of using two different hardware timers [26].

The ERC32 hardware provides two 32-bit timers (a very common arrangement on 32-bit boards) which can be programmed in either single-shot or periodic mode [4]. We use one of them as a timestamp counter and the other as a high-resolution timer. The former provides the basis for a high resolution clock, while the latter offers the required support for precise alarm handling.

Given that the maximum timestamp count that can be stored in the hardware clock is equal to 2**32 system clock ticks (215 seconds for a 20 MHz ERC32 board), which is largely insufficient for fulfilling Real-Time Systems Annex requirements [1, D.8 par. 30] of a minimum range of 50 years, a mixed hardware-software clock has been devised.

Time is represented as a 64-bit unsigned integer number of clock ticks. The hardware clock interrupts periodically, updating the most significant part (MSP) of the clock, a 32-bit unsigned integer kept in memory, while the least significant part (LSP) of the clock is held in the hardware clock register.

The 64-bit clock value very easily and efficiently, by simply concatenating the the MSP 32-bits, stored in memory. and the value stored within the hardware counter as the LSP 32-bits. Efficiency is achieved by using 32-bit operations instead of 64-bit ones (ERC32 does not provide 64-bit hardware operations). Each half of a *Time* value (MSP and LSP) is handled separately.

An efficient high resolution timer is achieved by programming the hardware timer on demand, and not periodically.

5.2 Interrupt handling

The three major goals when designing the interrupt handling mechanisms where simplicity, efficiency, and low interrupt latency.

Simplicity and efficiency are achieved by taking advantage of the Ravenscar restrictions on a single processor system; protected procedures (together with a short prologue and epilogue) are used as low level interrupt handlers, and no other intermediate synchronisation code is required.

Thanks to the use of the ceiling locking policy, the Ravenscar profile prevents the caller from getting blocked when invoking a protected procedure. The priority of a protected object which has a procedure attached to an interrupt must be at least the hardware Interrupt_Priority of that interrupt (otherwise the program is erroneous), as it is stated in the Systems Programming Annex [1, C.3.1 par. 14].

As a result, for as long as the active priority of the running task is equal to or greater than the one of an interrupt, that interrupt will not be recognised by the processor. On the contrary, the interrupt will remain pending until the active priority of the running

task becomes lower than the priority of the interrupt, and only then will the interrupt be recognised and processed.

If an interrupt is recognised, then the call to the protected procedure attached to that interrupt cannot be blocked, as the protected object cannot be in use. Otherwise the active priority of the running task would be at least equal to the priority ceiling of the protected object, which cannot be true because the interrupt was recognised.

Low interrupt latency is accomplished by allowing interrupt nesting; otherwise, interrupts would be disabled until control returns back to the interrupted task, and interrupt latency would be high since high priority interrupts would not be handled while low priority interrupts are serviced.

How stacks are organised is a critical issue when designing a nested interrupt handling mechanism. The simplest approach is to borrow the stack of the interrupted task. The problem with this approach is that it artificially inflates stack requirements for each task since every task stack would have to include enough space to account for the worst case interrupt stack requirements, in addition to its own worst case usage.

This problem is addressed by providing a dedicated "interrupt stack" managed by software. There are two fundamental methods that can be adopted. The first uses a single stack for all interrupts, and the second uses multiple stacks (the multiple stack method uses a stack for each interrupt). The single interrupt stack approach has two major disadvantages:

- It forces context switches to be delayed until the moment when the outermost interrupt (lowest priority interrupt) has finished its execution (see ORK documentation [22] for details), because otherwise interrupt handling is left in an inconsistent state. Hence, tasks which are unblocked as a result of interrupt handling may be artificially preempted by the execution of interrupts with a lower priority (priority inversion).
- It introduces an asymmetry in the way dispatching operations are executed. When a context switch is required, it is needed to check first whether we are in an interrupt handler before we actually proceed with the context switch.

The total size of the different interrupt stacks should be similar to that of the single interrupt stack, assuming that appropriate worst case analysis for maximum nesting has been accomplished for the single interrupt stack.

The multiple stack method solves the priority inversion problem that we could find with the single interrupt stack approach. By having different stacks for the different interrupts we can simply save the state of the interrupted task. Exiting from the current interrupt stack may be delayed after the context switch (until the interrupted task is executed again).

5.3 Context switch

The Ravenscar profile provides the basis for the implementation of deterministic and time analysable applications, but to perform a precise schedulability analysis of a Ravenscar compliant application, the context switch time must be deterministic [24]. In addition, efficiency enhances system schedulability, and simplicity allows for cost-effective certification of the run time.

Efficiency has been enhanced by limiting the number of hardware registers that are saved/restored every context switch (ERC32 has 128 integer registers and 32 floating point registers accessible to the user).

The ERC32 architecture (a SPARC V7) includes the concept of register windows[4, 21]. There are two different approaches to follow for the flushing policy: either to flush all register windows or just the windows currently in use [5]. Taking advantage of the execution points at which it is not necessary to save (and also not necessary to restore) the entire state of the machine [20], the run time adopts the latter approach so as to reduce the excessive overhead of saving and restoring unused window registers. Hence, all the register windows that have been modified between two consecutive context switches are flushed on the task stack, and the new windows are loaded with the contents of the stack corresponding the the task that is about to execute.

Not only efficiency, but also the predictability of execution is a crucial concern. The worst case execution time (WCET) of the two alternative approaches is approximately the same. The adopted implementation however exhibits a better average execution time. This is of no use for timing and scheduling analysis though, which must by definition use only WCET values. Note that by automatically saving/restoring all the register windows that have been used by tasks has one interesting advantage which is predictability; before and after the context switch the state of the different register windows (as well as the current window pointer and the window invalid mask) are the same.

Another issue that has been taken into account is that not every task (and certainly not every interrupt handler) use the floating point unit. Thus, the floating point context is not flushed until necessary. The floating point state remains in the floating point registers, and does not change until another task (or interrupt handler) tries to use the floating point unit.

The ORK implementation always saves/restores the floating point registers when performing a context switch [22], leading to non-negligible performance penalties. In the case of interrupt handlers, the floating point context is saved and restored each time an interrupt is recognised, to allow user handlers the use of the floating point unit safely.

The scheme that we implement is that floating point arithmetic is disabled by default (both for tasks and interrupt handlers). Then, when getting a floating point trap the handler takes care of saving and restoring what is needed. It means that the floating point unit is disabled after every context switch, in order to avoid saving the context of the floating point unit when it is not needed.

This way, tasks and interrupt handlers that do not use the floating point unit do not have the unnecessary overhead related to saving/restoring the floating point context. Moreover, when computing worst case execution times (WCET) the overhead associated to saving and restoring the floating point context needs to be accounted only when a task (or interrupt handler) is about to use the floating point unit.

The interrupt latency is also reduced because interrupt handlers do not save the floating point context; only the integer context is saved in order to process interrupts.

6 Related work

This project builds on some of the results of previous ESA projects which resulted in the development of ORK [9, 25]. Among others, the GNAT Pro for ERC32 compiler has the following advantages compared to ORK:

- The configurable run time capability allows for a fine grained selection of run-time entities.
- Duplicated and redundant code and data has been eliminated. Since the run time provides most of the functionality needed for tasking, some code and data are present both in the ORK kernel and in the GNAT Pro run time. Currently there is no separate kernel but a complete Ada run-time system with the needed information stored at the required level.
- Static creation of task descriptors and stacks (see Section 4.1). The compiler has been modified so that all tasking related data is created at compile time, removing the need for dynamic memory at run time.
- Task creation and activation has been largely simplified by means of adopting the Ravenscar profile restrictions.
- Several restricted exception models (see Section 4.3) are currently supported offering a wide range of choices which are with the recommendations made by the ISO 15942 [17] technical report.
- More efficient and deterministic context switches and interrupt handling. This part of the BSP has been redesigned in order to attain the simplicity and determinism required by high integrity real-time applications.
- ORK is based on a very old GNAT version (3.13), and there have been a lot of features added since then, such as a full-featured software development environment, a more efficient back-end code generator, etc.
- The validation test suite has been largely increased, including code coverage analysis (with the objective of achieving 100% statement coverage).
- Professional support and online consulting for Ada software development.

In order to have an idea of the simplification attained, it can be said that the ORK kernel is made up by around 1500 lines of Ada code (plus around 500 assembly lines), while the GNAT Pro equivalent functionality is currently implemented with around 1000 lines of Ada code (and less than 400 of assembly).

Additionally, comparing the size of a simple tasking program (including both data and code, but excluding stacks and the trap table), the resulting footprint with GNAT Pro for ERC32 (using the high integrity Ravenscar run time) is around 10KB, while the same executable compiled with ORK has a footprint of around 175KB.

7 Conclusions and future work

The Ravenscar profile defines an Ada subset that excludes non-deterministic and non analysable tasking features. In addition, features with a high overhead or complexity are also removed, allowing for a great simplification in the required run time. It allows for a 10KB footprint for a simple tasking program.

The fully configurable and customisable run-time library allows for a fine-grained selection of run-time features so that the footprint and complexity of the run time can be limited. This approach gives great control of the scope of certification activities, allowing for a cost-effective use in safety-critical applications where evidences of predictability, reliability, and safety must be generated. Additionally, full source code is included.

The run time has been carefully designed to isolate target dependencies, allowing its portability to new embedded architectures. We have plans for porting this work to other targets.

GNAT Pro for ERC32 is a flexible solution for large, safety-critical systems using the Ravenscar profile, allowing for developing multitasking systems for mission-critical space applications with safety requirements.

Acknowledgements

This work would not have been possible without the kind interest of Morten Rytter Nielsen, who initiated the project at the European Space Agency and supervised it as the Agency Technical Officer.

Many people at AdaCore have been involved into this project to some extent. This includes in particular Jerome Guitton and Arnaud Charlet. All my thanks to them for their support, suggestions, and reviews.

I would also like to thank the team of the Real-Time Systems Group at the Technical University of Madrid, specially to Juan Antonio de la Puente, for his help with the documentation, and Juan Zamorano, for his contributions to many design and implementation details.

Finally, I want to express my gratitude to IPL, for porting and making available *AdaTEST 95* to the *GNAT Pro for ERC32* compiler so that code coverage analysis could be achieved.

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