RIOT-POLICE: An implementation of spatial memory safety for the RIOT operating system

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Abstract

We present an integration of a safe C dialect, Checked C, for the Internet of Things operating system RIOT. We utilize this integration to convert parts of the RIOT network stack to Checked C, thereby achieving spatial memory safety in these code parts. Similar to prior research done on IoT operating systems and safe C dialects, our integration of Checked C remains entirely optional, i.e. compilation with a standard C compiler not supporting the Checked C language extension is still possible. We believe this to be the first proposed integration of a safe C dialect for the RIOT operating system. We present an incremental process for converting RIOT modules to Checked C, evaluate the overhead introduced by the conversions, and discuss our general experience with utilizing Checked C in the Internet of Things domain.

1 Introduction

RIOT is an operating system explicitly targeting "constrained IoT devices" [2, p. 2453]. As such these devices are programmed in the low-level programming language C [2, p. 2454] which offers very few safety features.

The result is that errors in programs written in C often go unnoticed [6, p. 103]. This is especially critical in the Internet of Things for a variety of reasons. First of all, debugging of constrained IoT devices is difficult [15, p. 1]. If a bug has been found, debugged and fixed an update needs to be provided. Unfortunately, updating constrained devices is challenging [16] and at the time of writing RIOT doesn’t provide any built-in method for doing so [1]. Additionally, some programming errors caused by missing safety features can be exploited. Buffer overflows are the standard example for this [5]. This is even more problematic on constrained IoT devices where protection mechanisms such as fault isolation are not available [14, p. 234].

For this reason, it is important to prevent such errors in the programming language itself. Doing so has been a longstanding research topic [6, 8, 36, 17]. One of the more recent research projects in this regard is an extension of the C programming language called Checked C [20]. In this paper we will present an integration of the Checked C language extension for the RIOT operating system. With this integration we are hoping to bring spatial memory safety to the RIOT operating system. To our knowledge, this is the first work exploring Checked C in the embedded domain. Our integration of Checked C remains entirely optional, thereby allowing utilization of Checked C without loosing the ability to compile RIOT with a legacy C compiler.

2 Background

The following subsections briefly introduce the technologies used in this paper. Related work is also presented.

2.1 Checked C

Checked C is an extension of the C programming language. It extends the C programming language as standardized by the ISO [10] (referred to as legacy C in the following text) with facilities to make writing spatial memory safe C code possible. Spatial memory safety ensures that "any pointer dereference is always within the memory allocated to that pointer" [20, p. 1].

Since it introduces new syntactic keywords, Checked C code needs to be compiled with a custom compiler based on LLVM/Clang. It cannot be compiled with a standard legacy C compiler such as GCC. Nonetheless, it has a strong focus on backwards compatibility allowing developers to call legacy C code from Checked C code and vice versa [20, p. 2]. Additionally, evaluations of the code emitted by the Checked C compiler have shown that the language extension introduces a comparably low executable size of 7.4% on average [20, p. 10]. This makes Checked C especially well suited for constrained IoT devices where program memory is often limited [2, p. 2453].
2.2 RIOT OS

RIOT OS is an open source real-time operating system for the Internet of Things. It supports constrained IoT devices with at least 1.5 kB of RAM and 5 kB of ROM. Nonetheless, it has features known from conventional operating systems. For instance, it supports multi-threading and provides a network stack [2, p. 2454].

Compared to other operating systems for the Internet of Things, for example Contiki [7] or TinyOS [13], RIOT is written entirely in standard ISO C [2, p. 2454]. As such, it is not memory safe and subject to bugs caused by memory safety violations such as buffer overflows. Unsurprisingly, out-of-bounds buffer accesses have been found in RIOT and fixed in the past [11, 12, 35, 33]. Unfortunately, the RIOT developers don’t gather these issues in a central place. Therefore, it is difficult to generate statistics for these kinds of bugs.

2.3 Related work

Various attempts have been made in the past to bring memory safety to different operating systems for the Internet of Things. Cooprider et al. tried to achieve memory safety by integrating Deputy into the TinyOS ecosystem [4] (referred to as Safe TinyOS in the following text). A similar approach, also utilizing Deputy, was implemented by Dunkels et al. for Contiki [7] (referred to as Safe Contiki OS in the following text). Especially the former research lead to some interesting results indicating a ROM overhead of 13% and a CPU overhead of 5.2% on average [4, p. 2].

To our knowledge no attempts haven been made to bring similar techniques to the RIOT operating system. Whether or not this is possible is subject of this paper. Contrary to the two approaches introduced above we decided to use Checked C instead of Deputy mainly because the latter is no longer maintained.

3 RIOT-POLICE Overview

RIOT-POLICE is a fork of the RIOT operating system which includes support for the Checked C language extension. It was initially based on release 2018.01 of the RIOT operating system but later updated to the 2018.04 release.

The RIOT source code itself is split into various software modules. Modules which should be included in an application are selected using a variable in the applications Makefile. The selected modules and the application code itself are compiled in alphabetic order and linked into a single freestanding binary. The Checked C toolchain had to be integrated into this existing build process.

Apart from build system integration, we also had to convert the legacy C code to Checked C. Regarding this process our goal was not to convert the entire RIOT code base since this would (a) be rather time consuming and (b) our assumption was that some parts of the code base (e.g. drivers) would not profit as much from memory safety as others. Since we deemed the network stack to be the largest attack vector, we decided to focus on that.

Within a few months we managed to convert RIOT modules for IPv6 [9], UDP [19], CoAP [21] and various utility modules of the network stack to “checked program scope” [22, pp. 18 sqq.]. Checked C guarantees that no spatial memory safety violations occur in checked program scope [20, p. 4]. Nonetheless, we wanted to continue using the converted modules from legacy C in order to convert RIOT modules incrementally. We achieved this through a Checked C language feature called “bounds-safe interfaces”. The Checked C compiler inserts “implicit conversions between checked types and unchecked types at bounds-safe interfaces” [22, p. 91], thereby ensuring that calls to checked functions type check even in legacy C code.

Additionally, we wanted to make using Checked C entirely optional. This was also an objective of the Safe Contiki OS project [18, p. 170]. Our reasoning behind this was as follows:

1. RIOT supports platforms not supported by LLVM/Clang and therefore unsupported by the Checked C compiler.
2. Some platforms are too constrained for runtime overflow checks.
3. RIOT is a large open source project with many contributors. Migrating all developers to a Checked C toolchain was not deemed feasible.

We achieved optional safety by defining macros for all new keywords and types introduced by the Checked C language extension. These macros fall back to using legacy C types if the USE_CHECKEDC preprocessor macro is unset. This allows compilation with a legacy C compiler which doesn’t understand the new keywords and types introduced by the Checked C language extension.

The source code for RIOT-POLICE is available freely on GitHub https://github.com/beduino-project/RIOT-POLICE.

4 Evaluation

In the following section we will briefly describe the experience we acquired by integrating Checked C into the RIOT ecosystem. Furthermore, we are going to evaluate the choices we made regarding this integration.

4.1 Optional safety through macros

The first and most important choice we made is that we wanted to make using Checked C entirely optional. The
We choose the former because previous research by Paul and Kumar used Deputy instead of Checked C they were able to elide Deputy annotations by defining macros without arguments for Deputy keywords [18, p. 170]. With Checked C this wasn’t possible since it introduces both new types and keywords. New keywords need to be stripped and checked types need to be mapped to legacy C types before compilation with a legacy C compiler we had to encapsulate the colon character, used to introduce a Checked C annotation, in the macro argument. In our experience, this makes it harder to figure out where the annotation starts on first sight. However, without modifications we wouldn’t have been able to use it even if we had wrote vanilla Checked C code since it currently doesn’t support bounds-safe interfaces [28]. The reasons why bounds-safe interfaces were required are explained in section 3.

It would have been possible to spend more time on automating the conversion process by improving this tool. Apart from issues related to the conversion process itself, we also noticed that our macros made the source code less readable. As an example, consider the two bounds-safe interfaces declared in Figure 2. The first bounds-safe interface is declared using vanilla Checked C, the latter using our macros. In order to hide Checked C keywords from a legacy C compiler we had to encapsulate the colon character, used to introduce a Checked C annotation, in the macro argument. In our experience, this makes it harder to figure out where the annotation starts on first sight. However, readability issues are not only related to our macros but also to Checked C itself. For instance, bounds-safe interfaces occasionally require types to be declared twice. As an example consider the annotation for the stream argument in Figure 2.

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It must also be mentioned that our macros might make it harder for new developers to learn Checked C since they need to learn both vanilla Checked C and our macros. Adjusting code using our macros without a basic understanding of Checked C isn’t possible. For example, a developer adjusting the definition in Figure 2 must be aware that the annotation of the stream argument needs to be updated when changing its type. Otherwise compilation will fail but only when compiling with a Checked C compiler, which makes it likely that these sort of mistakes will go unnoticed.
4.2 Checked C

Apart from issues we had with our macro system we also discovered a few issues with Checked C itself. The biggest issue being related to the fact that the compiler is "not recommended for production use" [3] yet. Especially the bounds-safe interfaces feature didn’t seem well tested yet. Over the course of a few months we found eight compiler bugs [23, 30, 31, 29, 25, 27, 26, 32]. Four of these were compiler crashes and almost all of them were related to bounds-safe interfaces. It must, however, also be noted that all compiler crashes reported by us have been fixed by the Checked C developers since.

Additionally, it occasionally became obvious that optional safety was not a Checked C design goal. For example, when converting the CoAP implementation nanocoap to Checked C we noticed some issues with the checked pointer type nt_array_ptr. This type ensures that the array referenced by the pointer is always null-terminated. This property is achieved by initializing it with a null-terminator and preventing overwrites of the terminator. However, when compiling with a legacy C compiler the array usually needs to be explicitly initialized with a null-terminator, for instance using memset(&ary, 0, sizeof(ary)). This code won’t compile with a Checked C compiler since it would overwrite the null-terminator. This is unfortunate since it makes the conversion process more complicated. It would be desirable for Checked C to allow overwriting the existing null-terminator with a new one [24]. As a workaround we used a preprocessor #ifdef statement to disable these memset(3) invocations when compiling with a Checked C compiler.

Furthermore, the executable size overhead we observed was higher than expected. We evaluated the overhead in executable size, introduced by the Checked C language extension, by compiling the RIOT application examples/nanocoap for the platform pba-d-01-kw2x with- and without optional safety features. Afterwards, we compared the size of the .text sections of the various ar(1) archives for modules we converted. The results are shown in Table 1.

The change in the size of the .text section is difficult to compare with benchmarks done by the Safe TinyOS and Checked C developers [4, p. 2, 20, p. 10] due to the fact that different programs were converted for benchmarking. Additionally, some of the modules we converted were rather small (e.g. pkt) and made heavy use of pointers. Nonetheless, the total percentage of observed overhead in executable size seems rather high with 37% in total, especially compared to the average increase in code size of 7.4% observed by the Checked C Developers [20, p. 10] or the 5.2% overhead on average achieved by the Safe TinyOS project [4, p. 2]. The fact that RIOT currently compiles all modules without link-time optimisation is a probable cause. Additionally, we didn’t optimize our Checked C code in a way that would allow the compiler to prove more bounds-checks to be redundant at compile-time.

The fact that the executable size overhead is rather high made it even more worthwhile to make the safety features entirely optional, especially due to the fact that RIOT supports quite a few platforms with tight limits regarding the available code size.

### Table 1: Executable size benchmark results

| Module    | LC (B) | CC (B) | ES (%) |
|-----------|--------|--------|--------|
| inet_csum | 80     | 134    | 68     |
| netapi    | 266    | 334    | 26     |
| netreg    | 212    | 370    | 75     |
| icmpv6_echo| 204    | 314    | 54     |
| icmpv6    | 304    | 516    | 70     |
| ipv6      | 1462   | 1819   | 24     |
| pkt       | 16     | 30     | 88     |
| pktbuf_static | 1126 | 1530   | 36     |
| udp       | 588    | 776    | 32     |
| Total     | 4258   | 5832   | 37     |

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5 Conclusion

We successfully integrated Checked C into an existing legacy C ecosystem and started converting RIOT incrementally from legacy C to Checked C. Even though not originally intended by the Checked C developers, it is also possible to retain compatibility with existing legacy C setups by making Checked C features optional through C preprocessor macros. This makes it possible to sustain support for IoT devices which are too constrained for runtime overflow checks. This was especially worthwhile since the executable size overhead indicated by our benchmarks was higher than expected.

We consider Checked C a promising technique for improving the security of existing legacy C software used on constrained devices. Nonetheless, we didn’t propose integrating our changes to RIOT developers because Checked C itself is still a moving target and the compiler is currently “not recommended for production use” [3]. However, this can also be seen as an advantage as it allows the Checked C developers to address some of the issues laid out in this paper.

One of those issues is missing tooling support for bounds-safe interfaces [28]. Future work should thus focus on improving tooling for bounds-safe interfaces and our macro system. In this regard it might be worthwhile to evaluate whether some of the issues we had with our macro system can be circumvented by writing vanilla Checked C instead and converting it to legacy C using a custom C preprocessor. Additionally, future research...
should focus on further reducing the executable size overhead we observed in order to also support highly constrained IoT devices.

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