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iSotEE: A Hypervisor Middleware for IoT-Enabled Resource-Constrained Reliable Systems

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ABSTRACT Embedded systems for critical applications are often based on resource-constrained devices to meet the requirements like performance predictability and energy consumption. To deal with the increased software complexity, many of these systems have adopted reliable RTOSes (Real-Time Operating Systems) with advanced protection functionalities. Meanwhile, the concept of IoT (Internet of Things) is gaining momentum. Many IoT OSes, specialized to provide the large software stack required by IoT applications, have been released. Nevertheless, neither reliable RTOS nor IoT OS can satisfy all the requirements of IoT-enabled reliable systems. Dual-OS configuration (i.e. the coexistence of reliable RTOS and IoT OS) is a promising approach to achieve high reliability and productivity simultaneously. Existing dual-OS solutions, however, depend on additional hardware features (e.g. virtualization extensions, ARM TrustZone), which are unavailable in most resource-constrained devices. This paper presents iSotEE (iSolated Execution Environment), a middleware allowing IoT OS to run inside an isolated environment on top of a reliable RTOS without special hardware. Open-source implementations of iSotEE for Renesas RX (with TOPPERS/HRP3 as reliable RTOS, Amazon FreeRTOS as IoT OS) and ARMv7-M (with two configurations of Zephyr as reliable RTOS and IoT OS) architectures are provided and evaluated. The results show that iSotEE can create reliable systems with a small footprint for resource-constrained devices, high real-time performance for critical applications, and high productivity and throughput for IoT applications.

INDEX TERMS Embedded software, Internet of Things, real-time systems, reliability.

I. INTRODUCTION

Embedded systems have been widely used to support critical applications such as industrial control [1], medical devices [2] and national infrastructures [3]. Typically, these systems are required to operate in harsh environments continuously (e.g. for years) and reliably (e.g. ultra-low unrecoverable error rate) [4]. To meet the SWaP-C (size, weight, power and cost) constraints, many embedded systems are based on hardware devices with very limited resources (known as "resource-constrained devices") [5]. Moreover, hard real-time performance is important when critical applications interact with the physical world [6]. The processors in resource-constrained devices have relatively simple and deterministic design, which can also offer advantages in guaranteeing real-time performance. For example, small on-chip memory can deliver lower latency and higher predictability than external memory [7].

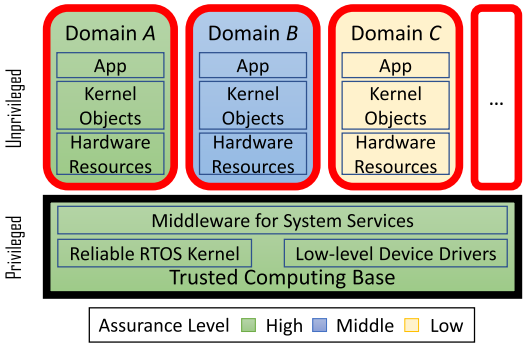

FIGURE 1. Example of the partitioned software in a critical system based on a reliable RTOS.

Critical systems must achieve high reliability because a failure could lead to severe consequences (e.g. human injury, property damage). Therefore, the development process

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typically requires the software to be sufficiently verified before releasing the products [8]. The verification cost is expensive and grows fast as the assurance level and software size increase [9]. Contemporary critical systems usually include multiple applications at different assurance levels [10]. Many of them have adopted RTOSes (real-time operating systems) with advanced features for high reliability (hereafter, "reliable RTOSes") to efficiently deal with the complexity [11]. The partitioning feature in a reliable RTOS, as shown in Fig. 1, allows isolating software components in different domains. Each domain only has access to the granted resources, and is prevented from interfering with another domain. It enables the containment of faults, which is essential to improve the reliability. The isolation also reduces the verification cost, since a domain can be verified separately according to its assurance level, and modifying one domain does not require the whole system to be reverified. The privileged components can access all resources, and are often referred to as the TCB (Trusted Computing Base). The TCB always has the highest assurance level since the reliability of such a system depends on its correctness. Therefore, to keep the verification process affordable, the TCB must be stable (i.e. less frequently updated) and small.

Meanwhile, the concept of IoT (Internet of Things) is gaining momentum in resource-constrained critical systems, because connecting those devices to the Internet has many benefits [12]. Monitoring and managing devices from the cloud can efficiently improve the maintainability and availability [13]. Big data analytics is helpful for creating smart and optimized services [14]. Over-the-air (OTA) updating allows the software to be patched faster, which mitigates the risks of bugs and vulnerabilities [15]. These connected devices, however, are also becoming attractive targets of cyberattacks since they can access valuable assets and sensitive data [16]. Therefore, adding IoT features to a critical system imposes a higher requirement on the reliability.

Building an IoT application typically needs a lot of components (e.g. middleware, device drivers) for common features like connectivity and secure communication. These necessary components are very complex, and thus developing them from scratch could be expensive and time-consuming. Some operating systems specialized for IoT-enabled resource-constrained devices (hereafter, "IoT OSes") have been released [17]. IoT OSes generally provide a software stack with many useful components to enable efficient application development. Several of them are further officially supported and maintained by cloud service providers for collaborative ecosystems [18]. Reusing the components from open-source IoT OSes can save the effort in building an IoT-enabled critical system greatly, but the conventional ad hoc reuse approach, as shown in Fig. 2, is very inefficient due to the following issues.

- **Low productivity.** IoT OS and reliable RTOS usually use different kernel and subsystem APIs [19]. Besides, the components in IoT OS are often updated very frequently, compared to the traditional components in a critical system. Porting and maintaining them for a reliable RTOS requires a considerable effort, which can lead to low productivity.
- **Reduced reliability.** Low-level components are typically designed to run in the kernel space to provide system services. Their large size can significantly bloat the TCB. Their complexity also increases the attack surface and creates many new security threats [20]. Adding these components will make a thorough verification of TCB difficult and costly.

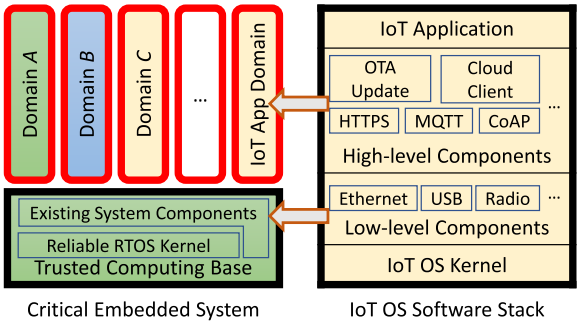


FIGURE 2. The conventional ad hoc approach of reusing software components from IoT OS in building an IoT-enabled critical embedded system.

Dual-OS configuration is a promising approach to efficiently reuse an IoT OS [21]. By using a hypervisor, a non-trusted OS (e.g. IoT OS and its applications) can execute in an environment isolated from the trusted OS (e.g. reliable RTOS). The critical services and sensitive data in the trusted side are protected against potential threats in the non-trusted side. The components for IoT are still running on the IoT OS kernel, and thus it is unnecessary to port them for the reliable RTOS. The whole IoT OS software stack is in a less privileged domain rather than the TCB. While Dual-OS configuration can overcome the issues in the ad hoc approach, existing solutions depend on additional hardware features such as ARM TrustZone and virtualization extensions [22]. These features are unavailable in most resource-constrained devices and thus we propose a new dual-OS solution.

The main contributions of this paper are summarized as follows:

1) iSotEE, a middleware allowing IoT OS to run inside an isolated environment on top of a reliable RTOS, is proposed. It is specially designed to meet the requirements of resource-constrained reliable systems.
2) Open-source implementations of iSotEE for Renesas RX and ARMv7-M architectures are provided. The RX target uses TOPPERS/HRP3 as reliable RTOS and Amazon FreeRTOS as IoT OS. The ARMv7-M target uses two different configurations of Zephyr as reliable RTOS and IoT OS. To our knowledge, iSotEE is the first dual-OS solution for RX processor family.
3) These implementations have been evaluated with multiple important metrics for IoT-enabled resource-constrained reliable systems, such as TCB size, productivity, footprint, overhead, and throughput.

TABLE 1. Development boards for IoT-enabled resource-constrained devices.

Board	Connectivity	Core	Architecture	RAM[a]	ROM[a]	MPU	MMU	Virtualization
Espressif ESP32-SOLO-1	Bluetooth, Wi-Fi	Xtensa LX6	Xtensa	520	448	✓	✓	✗
NXP LPC55S28-EVK	USB	Cortex-M33	ARMv8-M	256	512	✓	✗	TrustZone
Renesas Starter Kit+ for RX65N-2MB	Ethernet, USB	RX65N	RXv2	640	2048	✓	✗	✗
SiFive HiFive1 Rev B	*[External chip]*	SiFive E31	RV32IMAC	16	4096	✓	✗	✗
ST NUCLEO-F413ZH	USB	Cortex-M4F	ARMv7-M	320	1536	✓	✗	✗

[a] In kilobytes.

TABLE 2. Comparison of operating systems for resource-constrained devices.

	Category	Features for Critical Applications			Features for IoT Applications		
		Partitioning	Timer	Clock Sync.	Middleware	Protocol	Cloud
TOPPERS/HPR3	Reliable RTOS	Space, Time	μs	✓	*[Out-of-tree]*	*[Out-of-tree]*	*[Out-of-tree]*
Zephyr (LTS 1.14)[a]	Reliable RTOS	Space	ms	✗	*[Out-of-tree]*	*[Out-of-tree]*	*[Out-of-tree]*
Zephyr (LTS 1.14)[b]	IoT OS	✗	ms	✗	GUI, Network, Storage, USB	BLE, LWM2M, MQTT, TCP/IP	*[Out-of-tree]*
Amazon FreeRTOS	IoT OS	✗	ms	✗	Network	BLE, MQTT, TCP/IP	AWS
Azure RTOS	IoT OS	✗	ms	✗	GUI, Network, Storage, USB	TCP/IP	Azure
Mongoose OS	IoT OS	✗	ms	✗	Network, Storage	BLE, MQTT, TCP/IP	AWS, Azure, GCP

[a] Configured as reliable RTOS for safety-critical applications.
[b] Configured as low-overhead OS with connectivity for IoT applications.

The rest of this paper is structured as follows. Section II introduces necessary background. Section III explains the design of iSotEE in detail. The implementations for two targets are described in Section IV and evaluated in Section V. Section VI compares iSotEE with latest related work. Finally, Section VII concludes this paper and discusses some future work.

II. BACKGROUND

In this section, we first overview the hardware characteristics of IoT-enabled resource-constrained devices. The features of different operating systems for resource-constrained devices are then explained.

A. IOT-ENABLED RESOURCE-CONSTRAINED DEVICES

Resource-constrained devices in this paper mainly refer to those devices incapable of running GPOS (general purpose operating system) like Linux. As minimum requirements to build IoT-enabled reliable systems, the hardware should at least have some connectivity for IoT applications, and protection feature for critical applications.

Table 1 shows some representative development boards meeting the requirements above for different hardware architectures. Typically, these boards have limited RAM (a few hundred kilobytes) and ROM (several megabytes). While MPU (Memory Protection Unit) has been widely adopted, advanced features like MMU (Memory Management Unit) and hardware-assisted virtualization are unavailable to most processors.

B. OPERATING SYSTEMS FOR RESOURCE-CONSTRAINED DEVICES

As we have mentioned, both reliable RTOS and IoT OS can support resource-constrained devices. Table 2 compares the features of some open-source reliable RTOSes and IoT OSes.

TOPPERS/HRP (High Reliable system Profile) is a series of open-source μITRON-like reliable RTOS kernels widely used in Japan [23]. HRP3 (version 3 of TOPPERS/HRP series) not only provides space partitioning, but also supports industrial-grade critical applications with advanced features (e.g. time partitioning, μs high-resolution time management, external clock synchronization). However, to develop IoT applications, the user must port and maintain out-of-tree modules which can limit the productivity.

Zephyr [24] is a relatively new RTOS targeting connected resource-constrained devices. It can be flexibly configured to be used as a reliable RTOS or an IoT OS. Its IoT-related modules typically run in privileged mode, which can lead to large TCB size. These modules are not covered by Zephyr's current scope of safety certification. Therefore, to use Zephyr as a reliable RTOS for critical applications, the IoT features should be considered as out-of-tree due to expensive verification cost required. When using Zephyr as an IoT OS for non-critical applications, the partitioning feature can be disabled to reduce overhead.

Amazon FreeRTOS, Azure RTOS and Mongoose OS are three IoT OSes with official cloud collaboration support. All of them do not provide full-blown partitioning feature for critical applications. Unprivileged tasks in Amazon FreeRTOS can access all kernel objects via RTOS API. Only dynamic loaded modules in Azure RTOS have partitioned memory space. Mongoose OS is a flat RTOS (i.e. RTOS uses a flat memory model without any memory protection functionality).

III. THE DESIGN OF ISOTEE

iSotEE (*iSolated Execution Environment*) is a hypervisor specially designed to support dual-OS configuration on resource-constrained devices. It has many advantages for building IoT-enabled resource-constrained reliable systems as follows:

- **Portable and lightweight.** iSotEE is a portable middleware that can be implemented in most reliable RTOSes. It does not require additional hardware features and thus supports various processor architectures. It has a

lightweight design with a small overhead and footprint to satisfy the resource constraints.

- **High reliability with reduced TCB size.** The whole software stack of IoT OS, including interrupt handlers, runs in unprivileged mode. Therefore, those complex IoT-related middleware and device drivers can be excluded from the TCB to improve reliability and security.
- **Meet hard real-time requirements with reliable RTOS.** iSotEE assumes that reliable RTOS must support hard real-time applications while IoT OS is for soft real-time and best-effort applications. It allows the reliable RTOS to run natively and preempt the IoT OS to minimize the interference. The hypervisor itself is also optimized to reduce performance impact.
- **Increase productivity and throughput with IoT OS.** IoT OS only requires minor modifications to execute on iSotEE. Since there is no need to implement or port IoT software components for reliable RTOS, the development effort can be greatly saved. Further, IoT OS, due to the simplicity of its kernel, can potentially deliver higher throughput than reliable RTOS.

In this section, the architecture of iSotEE is explained at first. Some important concepts are further described later.

A. ARCHITECTURE OVERVIEW

Fig. 3 shows an overview of a reliable system with iSotEE. The architecture consists of several main components described as follows:

- **Host OS:** It is a reliable RTOS which must at least support space partitioning (e.g. memory protection). The predictability can be further improved if time partitioning is supported.
- **Guest execution environment:** It is an isolated domain created using the partitioning functionality of reliable RTOS. Programs executed in this domain are not trusted and can only access resources explicitly granted by the system designer.
- **Guest software:** It is the software stack for IoT, which runs on a host OS task inside the guest execution environment. It typically includes IoT OS kernel, interrupt handlers, device drivers, middleware and user applications.
- **iSotEE hypervisor middleware:** It provides necessary hypervisor services such as communication and device virtualization. It is implemented as a host OS system component running in privileged mode. More details will be explained later in this section.
- **Paravirtualization API:** It is a library for the guest to request services, such as interrupt management, provided by the hypervisor middleware. An existing IoT OS can be ported to iSotEE as a guest OS by implementing its BSP (board support package) using this API.

This architecture has some noteworthy characteristics:

- The reliable RTOS runs natively on bare metal, just like in a traditional reliable system. For hard real-time applications, the performance penalty can be small and predictable.
- Partitioning is an important yet complex part of resource management in a classic hypervisor design. iSotEE offloads it to the reliable RTOS, in order to make the hypervisor as lightweight as possible.
- Guest OS and its applications run in the same privilege level, which means there is no protection between them. This design can support most use cases since existing IoT OSes are typically based on flat RTOSes without protection. Further, the flat guest OS has the potential to deliver higher throughput than the reliable host RTOS due to smaller overhead.
- All guest software components run on a single host OS task. They are managed by the host as a whole, which can simplify the design and analysis of timing behavior. The host side footprint is also reduced since only a small and fixed amount of resource is required, regardless of the number of tasks in guest OS.
- IoT OS makes use of many open-source software components with various licenses to maximize productivity. Reliable RTOS, on the other side, may include certified/verified proprietary components to improve the reliability of critical applications. iSotEE allows the host and guest software to be separately linked as two independent binaries. This strong isolation can reduce the risk of license compatibility issues.

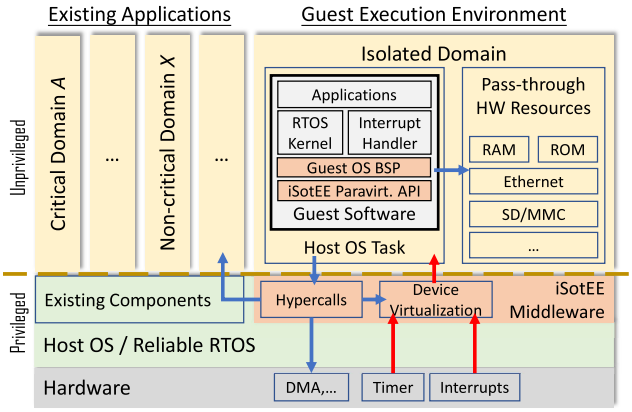


FIGURE 3. Architecture of reliable system with iSotEE hypervisor middleware.

B. RESOURCE MANAGEMENT

iSotEE allows the system designer to grant necessary hardware resources (e.g. memory, peripheral devices) to the guest execution environment. Three types of devices are supported to meet the needs in different use cases.

1) PASS-THROUGH DEVICES

The memory areas of these devices are assigned to the guest via the space partitioning functionality in reliable RTOS. The overhead is negligible since guest software can directly access them without the intervention of the host.

These devices must be assigned with caution since the access requests are not checked by the host. They should be exclusively used by the guest and improper access to them must not harm the host side.

2) PROTECTED DEVICES

Some devices can become attack vectors if they are improperly accessed by the guest. Using DMA (direct memory access) controller is a typical example, which must be checked to ensure that the guest does not access disallowed addresses. Protected devices are always accessed by the guest via the hypercall interface. While the overhead is larger than pass-through devices, improper access can be checked and blocked by the hypervisor.

3) VIRTUAL DEVICES

Devices for the guest must be virtualized if they behave differently than on the bare-metal environment. System tick timer and interrupt controller are two common virtual devices required by most, if not all, guest OSes. Devices shared between the host and guest, such as data storage, may also need virtualization in some cases. Extending an existing host-side device driver is a typical approach to implementing a virtual device. For example, the system designer can use host-aware hypercalls (described in Section III-C) to receive virtual storage service requests from guest OS and delegate them to the file system in host OS. To limit the guest's accessible files and storage usage, the hypercalls will check the permission for these service requests. In this case, it should be noted that the guest files are also accessible from the host OS, since they are actually stored in the host file system. Therefore, virtual devices implemented in this approach can be used for communicating between guest and host OS via the shared resources.

C. HYPERCALL INTERFACE

The hypercall interface provides a safe communication mechanism for the guest to request services from the hypervisor. A hypercall is analogous to a system call in the conventional OS, which is usually invoked via a software interrupt (a.k.a. trap instruction). It transfers the control to the privileged hypervisor to execute some trusted function, and then returns to the calling guest program. iSotEE supports two types of hypercalls as follows.

1) BARE-METAL HYPERCALLS

These hypercalls are directly executed without doing a context switch to the host OS. They are not allowed to use the host kernel services but the overhead can be reduced. During their execution, all (not only the guest's) interrupts are disabled to avoid the race condition caused by the host OS. This kind of hypercall must be short and predictable (e.g. a single write to some protected register), since long interrupt disabled time is harmful to hard real-time performance.

2) HOST-AWARE HYPERCALLS

The guest software can also use the host system calls for communication, since it runs on a host OS task. A hypercall via the system call interface is aware of the host system, and thus is able to provide more advanced service using the host OS API. A system call has larger context switch overhead than the bare-metal hypercall, but only disables the interrupts for a few cycles during its execution. For long and complex jobs, this kind of hypercall is more suitable since it has minimal impact on the host real-time performance.

From the perspective of the guest, both kinds of hypercalls can guarantee the atomicity.

A hypercall may also return a shared memory area (e.g. buffers, read-only data structures) to the guest, in order to communicate further with lower overhead.

D. GUEST OS SCHEDULER SUPPORT

The context switch procedures are essential to support an OS scheduler. Their implementations depend on the target hardware, and thus are usually included in the BSP. To schedule guest OS tasks on the host OS task specified by iSotEE, the native BSP for the guest OS must be modified as follows:

- Context switching will be performed when a task yields the control. It is protected with critical section since it must not be interrupted. Native critical sections are often created by locking CPU with privileged instructions (e.g. disable all interrupts). They must be replaced with implementations provided by the iSotEE paravirtualization API to support the unprivileged guest OS.
- For guest OS with preemptive scheduler, context switching may also be performed inside the interrupt handler. On entering a handler, the context (e.g. stack pointer, registers) of the virtual interrupt controller is different from the hardware controller. The native interrupt handler must be modified accordingly.

It is recommended to assign the lowest priority to the host OS task for guest software, so other host applications can always preempt the guest. The time partitioning feature, if supported by the host OS, can also be used to control the guest CPU usage, for better predictability.

E. VIRTUAL INTERRUPT CONTROLLER

A virtual interrupt controller is implemented by iSotEE to manage those interrupt sources assigned to the guest (hereafter, ''guest interrupts''). It also provides a mechanism to let the guest interrupt handler run on the unprivileged host OS task, just like those guest OS tasks. Some important concepts are explained in this section.

1) INTERRUPT PRIORITY

The guest interrupts should be assigned with lower hardware interrupt priority than other interrupts used by the host OS. By masking the highest priority of guest interrupts during running the host OS applications, the interference with the host can be prevented.

```
1:  procedure DeliverInterrupt
2:      irq is the arrived interrupt request
3:      Mask irq
4:      Acknowledge irq
5:      Put irq into the guest interrupt pending queue
6:      if the guest is not in critical section then
7:          tf is the guest trap frame
8:          bpc is a shared variable the guest can read
9:          bpc ← tf.pc                ▷ Backup program counter
10:         tp.pc ← the guest interrupt handler
11:         Set the guest interrupt-suppressed flag
12:     end if
13: end procedure
```

FIGURE 4. Deliver an interrupt request to the guest.

2) INTERRUPT-DISABLED CRITICAL SECTION

Critical sections can be created by disabling all guest interrupts. This approach typically uses hypercalls to change the interrupt priority mask. Its behavior is very similar to the native critical section since the interrupts are disabled at the hardware level. However, the hypercall overhead is relatively large compared to the native implementation.

3) INTERRUPT-SUPPRESSED CRITICAL SECTION

Critical sections can also be created using a shared flag variable. On entering a critical section, the guest atomically sets the flag. If a guest interrupt arrives when the flag is set, the hypervisor will put its request into a pending queue. On exiting a critical section, the guest atomically clears the flag and, if there is any pending interrupt, switches to the interrupt handler. This approach can suppress the interrupt handler without hypercalls, which has smaller overhead. However, the guest interrupts are not actually disabled and will be acknowledged by the hypervisor at first. Some devices have sensitive acknowledge timing requirements, which may be incompatible with this approach.

4) INTERRUPT DELIVERY

Fig. 4 shows how an interrupt request is delivered to the guest by the hypervisor. To support level-triggered interrupts and mitigate DoS (Denial of Service) attacks, the arrived request will be masked by the hypervisor, and should be unmasked by the guest after handling. The current running guest OS task can be interrupted if, and only if, the guest is not in critical section. In that case, the hypervisor will modify the trap frame of the host OS task running the guest software. By replacing the program counter (i.e. return address) in the trap frame with the guest interrupt handler address, the guest will switch to the handler on resuming execution. The original program counter is saved to a shared variable for the guest OS scheduler context switching. After modifying the trap frame, the guest is put into an interrupt-suppressed critical section, so the following requests will be simply added into the pending queue.

F. VIRTUAL SYSTEM TICK TIMER

In the native environment, an OS kernel typically uses a hardware timer for time management. The timer is set to trigger periodic interrupt requests (a.k.a. system ticks) to support preemptive scheduling. The system time (i.e. the elapsed time since the system is started) can also be calculated by counting the occurrence of system ticks.

For a guest OS, virtual system ticks can be easily generated by registering a cyclic handler in the host OS. The hypervisor delivers them to the guest like interrupt requests. However, it must be noted that the guest system time cannot be simply calculated from virtual ticks, because the guest OS may be preempted by the host for indeterminate periods of time. This issue can be handled using a shared variable to store the guest system time. The hypervisor will update it to the latest value (e.g. by deriving from the host system time) before delivering each virtual tick.

On hardware with adequate timer resource, the guest may also use two dedicated hardware timers, one periodic timer for ticking and one free-running timer for system time, to reduce the overhead. Meanwhile, timers can be exploited for side-channel attacks on some processor architectures, and should be assigned to the guest with caution [25].

IV. IMPLEMENTATION

We have implemented iSotEE on two representative IoT-enabled resource-constrained targets to evaluate our approach, and made the source code publicly available. Different host OSes, guest OSes and hardware architectures are used to show the high portability of iSotEE.

A. TARGET 1: RENESAS RX ARCHITECTURE

For this target, TOPPERS/HRP3 reliable RTOS is used as the host OS. It supports both space and time partitioning, and also provides advanced features for critical applications like high-resolution (in μs) time management.

Amazon FreeRTOS (version 201910.00) is used as the guest OS. It is an IoT OS based on the famous FreeRTOS kernel, including lots of middleware (e.g. network protocols, security libraries, over-the-air updating) for IoT applications [18]. It is officially supported by the AWS (Amazon Web Services) cloud. A collection of demo applications, named `aws_demos`, is provided to show the functionalities of Amazon FreeRTOS. Our implementation has also been tested with these applications.

Renesas Starter Kit+ for RX65N-2MB is used as the target board. It is one of the Amazon FreeRTOS-qualified hardware platforms suitable for various IoT applications [26]. It is based on 120 MHz RX65N SoC with constrained resources (RAM up to 640 KB, ROM up to 2 MB, no hardware virtualization support). The Renesas RX processor family has been adopted in many critical industrial systems, due to its low power consumption and high performance predictability. RX65N SoC provides a dedicated DMA controller, called EtherDMA, for Ethernet communication. Our implementation has supported EtherDMA as a protected device. To our knowledge, iSotEE is the first dual-OS solution for RX processors.

Fig. 5 shows an application scenario example of this target. iSotEE allows the developer to implement IoT services on

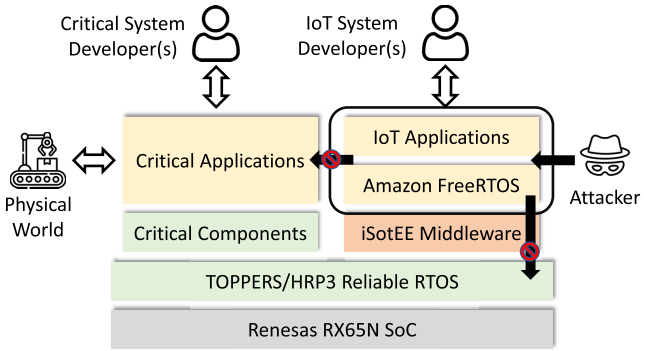


FIGURE 5. Application scenario example (target 1).

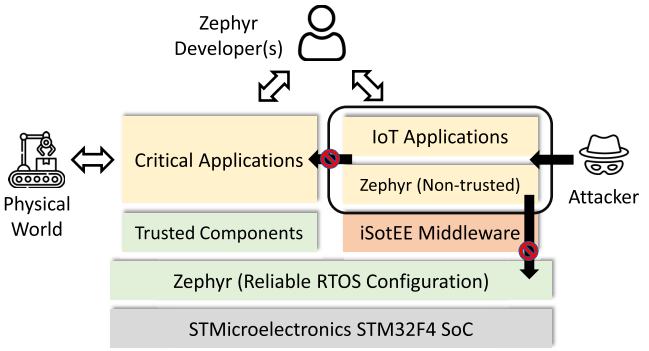


FIGURE 6. Application scenario example (target 2).

an IoT OS (Amazon FreeRTOS). For IoT applications, the development cost can be effectively reduced by utilizing the rich middleware from IoT OS. The critical applications are developed and natively executed on a reliable RTOS with guarenteed real-time performance. iSotEE runs the IoT OS in an unprivileged environment, and thus the critical services, which may interact with the physical world, can be protected against the potential security risk of the IoT service.

B. TARGET 2: ARMV7-M ARCHITECTURE

For this target, both the host OS and the guest OS run Zephyr (v1.14 LTS). However, the host OS uses a reliable RTOS configuration and the guest OS uses an IoT OS configuration.

The reliable RTOS configuration enables space partitioning feature (i.e. `CONFIG_USERSPACE`), but disables all IoT-related features to minimize the TCB size and reduce the attack surface, as discussed in Section II-B. The IoT OS configuration, on the other hand, is configured as a flat RTOS with IoT features. Since the guest OS is more lightweight than the host and runs in unprivileged mode, this combination of dual configurations can improve the performance and reliability.

ST NUCLEO-F413ZH is used as the target board. It is based on 100 MHz STM32F4 SoC (Cortex-M4F core, 320 KB RAM, 1.5 MB ROM). Its ARMv7-M architecture is very popular in both consumer and industrial resource-constrained devices. STM32F4 SoC provides USB connectivity, and our implementation allows the guest to work as a USB network gadget and a simple HTTP server.

Fig. 6 shows an application scenario example of this target. Zephyr provides system components for both critical and IoT applications. Because these system components run in privileged mode, they must be verified to ensure the reliability of a critical system. However, the IoT-related components are complex and thus the verification cost is very expensive. iSotEE allows the developer to use a non-trusted guest Zephyr OS for IoT services. Since these system components in the guest OS are isolated from the trusted critical components, it is unnecessary to verify them. This approach can effectively improve the reliability and reduce the verification cost of an IoT-enabled critical system.

V. EVALUATION

In this section, we discuss the characteristics of iSotEE for creating IoT-enabled resource-constrained reliable systems, by evaluating the implementations. For target 1 (RX architecture), the default CCRX compiler optimization settings are used for both host and guest software. For target 2 (ARMv7-M architecture), the default GCC ARM compiler optimization settings provided by Zephyr's build system are used.

A. SOFTWARE METRICS

We have measured the software metrics with a representative system configuration for each target. The guest OS runs IoT demo applications while the host OS runs system logging service. For target 1, the guest uses middleware for ethernet, TCP/IP, DHCP client and secure sockets to communicate with a server. For target 2, the guest uses middleware for USB device, ethernet, TCP/IP and secure sockets to build a simple HTTP server over USB. Table 3 shows the SLOC (source lines of code) of related components, with comments and blank lines excluded. Table 4 shows the memory footprint of host and guest binaries.

1) OBSERVATION 1: ISOTEE HAS A VERY SMALL TCB SIZE

The lightweight architecture, as described in Section III-A, can exclude the whole IoT software stack from the TCB by only adding less than 230 lines of code to the host software in both targets. It significantly reduces the system verification effort, and thus improves reliability and security.

2) OBSERVATION 2: ISOTEE INCREASES THE PRODUCTIVITY FOR IOT APPLICATIONS

A huge amount of IoT middleware components can run as guest software without any modification. In both targets, the host OS only requires a tiny patch to support the hypervisor middleware. Besides, Zephyr and FreeRTOS can be ported as guest OS by implementing a small BSP.

3) OBSERVATION 3: ISOTEE IS GENERIC AND LIGHTWEIGHT ENOUGH FOR RESOURCE-CONSTRAINED DEVICES

iSotEE does not require more hardware features compared to a reliable RTOS. Its components (i.e. hypervisor middleware,

TABLE 3. SLOC of iSotEE & guest in representative systems.

Category	Target 1		Target 2	
	Component	Lines of Code	Component	Lines of Code
Host Software (iSotEE-Related)	Host OS Patch (TOPPERS/HRP3)	22	Host OS Patch (Zephyr)	34
	Hypervisor Middleware	204	Hypervisor Middleware	178
Guest Software (iSotEE-Related)	Paravirtualization API Library	164	Paravirtualization API Library	137
	Guest BSP (for FreeRTOS)	266	Guest BSP (for Zephyr as IoT OS)	213
Guest Software (Unmodified)	FreeRTOS Kernel	7,230	Zephyr Kernel	6,665
	Middleware (Crypto, Network, ...)	138,769	Middleware (USB, Network, ...)	39,650
	Demo Applications (aws_demos)	6,167	Demo Application (http_server)	119

TABLE 4. Memory footprint of representative systems.

Binary	Component	Target 1		Target 2	
		RAM[1]	ROM[1]	RAM[1]	ROM[1]
Host	Hypervisor Middleware	36	671	45	753
	Guest Execution Environment	1,508[2]	692	1,060[3]	160
	Other (Kernel, Apps, ...)	11,610	49,981	23,471	68,451
Guest	BSP + Paravirtualization API Library	32	612	32	612
	Other (Kernel, Apps, ...)	180,980	369,986	41,032	97,048

[1] In bytes.
[2] User-configured stack size (384 bytes in the example) is included.
[3] User-configured stack size (512 bytes in the example) is included.

TABLE 5. Execution time of the paravirtualization API.

Operation	Target 1		Target 2	
	Hypercall	CPU Cycles	Hypercall	CPU Cycles
Enter interrupt-disabled critical section	Bare-metal	27	Bare-metal	62
Exit interrupt-disabled critical section	Bare-metal	22	Bare-metal	58
Enter interrupt-suppressed critical section	Unused	5	Unused	10
Exit interrupt-suppressed critical section	Unused	21	Unused	10
Mask a guest interrupt	Bare-metal	34	Bare-metal	84
Unmask a guest interrupt	Bare-metal	32	Bare-metal	83
Pop a guest interrupt from pending queue	Bare-metal	58	Unused	15
Read the virtual system timer value	Unused	5	Unused	10
Use EtherDMA to send a frame[a]	Host-aware	250		
Use EtherDMA to receive a frame[a]	Host-aware	487		
Configure clock for USB controller[b]			Host-aware	257
Skeleton bare-metal hypercall[c]	Bare-metal	17	Bare-metal	52
Skeleton host-aware hypercall[c]	Host-aware	145	Host-aware	145

[a] Only target 1 implements EtherDMA device.
[b] Only target 2 implements USB controller.
[c] Baselines measured for reference purpose.

TABLE 6. Host OS overhead introduced by iSotEE.

Reason / Purpose	Target 1		Target 2	
	Operation[a]	Overhead[b]	Operation[a]	Overhead[b]
Track guest trap frame for interrupt delivery	An interrupt preempts a task	+8	An interrupt preempts a task	+8
	Context switch between tasks	+6	A task resumes from an interrupt	+8
	A task yields the control	+7		
Mask guest interrupts when running host apps	A task starts execution	+1	Context switch between tasks	+13
	A task resumes execution	+1	A task yields the control	+14

[a] All tasks here refer only to host OS tasks.
[b] Measured in cycles.

guest execution environment, guest BSP linked with paravirtualization API library) have a small memory footprint in total. Further, in target 2, RAM usage of the whole system is less than 64 KB. It indicates that most resource-constrained devices capable of running a reliable RTOS can be supported.

B. PERFORMANCE OVERHEAD

The paravirtualization API is used by the unprivileged guest to request hypervisor services. Its execution time, as shown in Table 5, is important to the performance of guest OS.

1) OBSERVATION 4: THE PARAVIRTUALIZATION API CAN SUPPORT SOFT REAL-TIME IOT APPLICATIONS WITH REASONABLE PERFORMANCE

Most operations only cost less than 0.5 μs for target 1 (120 MHz CPU), and less than 0.9 μs for target 2 (100 MHz CPU). Accessing the EtherDMA protected device in target 1 is relatively complex and costs about 4 μs at most.

In many constrained industrial IoT scenarios, the network latency requirements are in the order of 10 milliseconds [27]. Therefore, we believe the performance is quite acceptable for soft real-time applications.

2) OBSERVATION 5: IT IS IMPORTANT TO USE DIFFERENT TYPES OF HYPERCALLS PROPERLY

The invocation overhead of a host-aware hypercall is multiple times (145 vs 17 in target 1, 145 vs 52 in target 2) of a bare-metal hypercall. Implementing hypervisor services with bare-metal hypercalls as possible can improve performance. Meanwhile, for long and complex operations (e.g. EtherDMA), host-aware hypercalls should be used to reduce the impact on the host real-time performance.

Table 6 shows the performance impact of iSotEE on the host OS, which is essential to those critical applications.

3) OBSERVATION 6: ISOTEE CAN SATISFY HARD REAL-TIME REQUIREMENTS OF THE HOST SOFTWARE

The guest interrupts are masked during the execution of host applications. Several operations in the host OS are patched to support the hypervisor but only small and predictable overheads are introduced. Masking interrupts is faster in target 1, because RX architecture has dedicated instruction to set priority level while ARMv7-M requires register access.

C. THROUGHPUT BENCHMARK

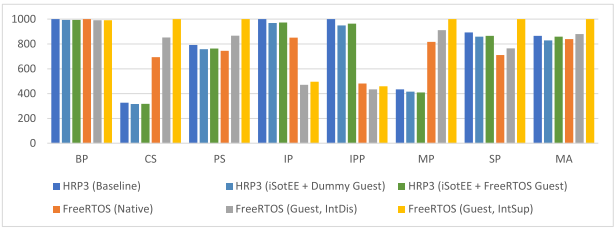
Thread-Metric is an open-source benchmark suite for measuring RTOS [28]. Each benchmark application repeatedly executes some test program for a period of time, and then outputs a counter value (i.e. the number of iterations). We use Thread-Metric to evaluate the throughput of a system with iSotEE. The results are shown in Fig. 7.

For target 1, the host OS is measured with three configurations: (1) HRP3 without iSotEE as baseline (2) HRP3 with iSotEE and a dummy (busy loop) guest (3) HRP3 with iSotEE and FreeRTOS as guest OS. The guest OS is measured with three configurations: (1) FreeRTOS in the native environment (2) FreeRTOS as a guest using interrupt-disabled critical sections (3) FreeRTOS as a guest using interrupt-suppressed critical sections.

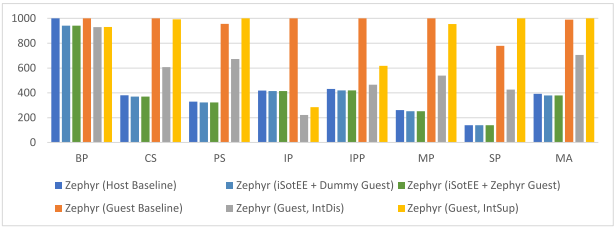
The target 2 is measured with similar configurations. Zephyr in the host side is configured as reliable RTOS kernel with space partitioning. Zephyr in the guest side is configured as flat RTOS kernel.

1) OBSERVATION 7: ISOTEE DEGRADES THE HOST THROUGHPUT SLIGHTLY

The overheads in Table 6 and virtual ticks in Section III-F will consume some CPU time. The maximum degradation is about 4% for target 1 (observed in IPP benchmark), and about 6% for target 2 (observed in BP benchmark). Different guests (dummy vs IoT OS) can present similar results, which indicates the degradation is mainly determined by iSotEE hypervisor rather than the executed guest software.



(a) Target 1



(b) Target 2

FIGURE 7. Normalized results of the Thread-Metric benchmark suite for throughput comparison, including BP (basic processing), CS (cooperative scheduling), PS (preemptive scheduling), IP (interrupt processing), IPP (interrupt preemption processing), MP (message processing), SP (synchronization processing) and MA (memory allocation).

2) OBSERVATION 8: HOST OS MAY SUPPORT CRITICAL APPLICATIONS WITH HIGHER THROUGHPUT

Critical applications, which tend to process interrupts frequently, run on the host OS by the iSotEE design. HRP3, like most reliable RTOSes, is optimized for better interrupt handling performance. IP and IPP benchmarks also confirm that HRP3 delivers high throughput compared to FreeRTOS. This cannot be observed in target 2 since the host and guest use same Zephyr OS with different settings.

3) OBSERVATION 9: GUEST OS SUPPORTS IOT APPLICATIONS WITH HIGHER THROUGHPUT

IoT OSes typically include many tasks to support various complex components such as network stacks. The performance of scheduling and messaging between tasks is important for IoT applications. Since FreeRTOS is a flat RTOS without protection between the kernel and applications, it has lower overhead than HRP3 reliable RTOS in many task operations. The idea is similar to *unikernel* [29] in cloud computing, which improves performance by using hypervisor to replace the OS protection functionality. CS, PS and MP benchmarks confirm that FreeRTOS guest delivers high throughput compared to HRP3. The differences are even more significant in target 2. It indicates that, although features of both reliable RTOS and IoT OS are provided by Zephyr, using them separately with iSotEE has remarkable benefits for reliability and performance.

4) OBSERVATION 10: USING INTERRUPT-SUPPRESSED CRITICAL SECTIONS CAN EFFECTIVELY IMPROVE THROUGHPUT

The overhead of interrupt-disabled critical sections, compared to interrupt-suppressed ones, is about twice in target 1

and six times in target 2. As a result, IntSup configuration shows significantly better throughput than IntDis in many benchmarks, for both FreeRTOS and Zephyr.

5) OBSERVATION 11: NATIVE FREERTOS IS OUTPERFORMED BY THE GUEST IMPLEMENTATION IN SOME CASES

This phenomenon can be observed in CS, PS, MP, SP and MA benchmarks. We have found that it is caused by inefficient context switch implementation in the native BSP. In FreeRTOS (Native), the cooperative scheduler (i.e. task yield) shares the same context switch procedure with the preemptive scheduler. It can simplify the implementation but also includes unnecessary operations. As described in Section III-D, the guest BSP should provide different context switch procedure for each case, which leads to better performance. The native BSP of Zephyr for ARMv7-M also shares the context switch procedure. However, the ARMv7-M architecture provides a hardware optimization for this purpose called PendSV. Therefore, the guest only shows slightly better performance in a few benchmarks like PS and SP.

VI. RELATED WORK

Dual-OS solutions can offer many benefits, since neither reliable RTOS nor IoT OS can satisfy all the requirements. Although hypervisor is a well-established technology for high-end embedded systems (e.g. those capable of running Linux), to our knowledge, iSotEE is the first open-source solution supporting low-end resource-constrained devices [30]. Due to this situation, we cannot quantitatively compare iSotEE with existing solutions under similar experimental conditions. Instead, to show the novelty of our solution, this section qualitatively compares iSotEE with the state-of-the-art related works on IoT-enabled embedded real-time systems (not limited to the resource-constrained environment).

ACRN [31] and Bao [32] are two latest open-source hypervisors for high-end embedded systems. ACRN is a Linux Foundation project under active development, and provides many advanced features for safety-critical embedded systems [33]. It relies heavily on Intel Virtualization Technology (Intel VT), and thus cannot be used on non-Intel platforms. Meanwhile, Bao has a portable design and supports two architectures (ARMv8-A and RISC-V). Both of them implement resource isolation via hardware-based approach, and thus their targets are limited to high-end processors with large memory size and virtualization support. On the other hand, iSotEE uses a software-based paravirtualization approach only depending on minimal hardware features (e.g. several kilobytes memory and MPU), which can support most processors for resource-constrained devices. Generally, the performance overhead and operating system modifications are two potential drawbacks of software-based paravirtualization. Our evaluation results have shown that iSotEE has small and predictable real-time performance overhead, and the modifications to host and guest OS are less than 300 lines of code.

MultiZone [34] and lLTZVisor [21] are two latest hypervisors for resource-constrained devices. MultiZone uses a software-based approach similar to iSotEE [20] and supports low-end RISC-V and ARMv7-M processors with MPU. Although MultiZone is able to run more than two OSes, all OSes are virtualized in unprivileged mode. Meanwhile, iSotEE allows the reliable RTOS to execute natively in privileged mode with hard real-time guarantee. lLTZVisor is a dual OS solution specially designed for ARMv8-M processors with TrustZone feature. It can also be extended to support multicore platforms [35]. As a hardware-based approach, it runs unmodified reliable RTOS and IoT OS with native performance, but the lack of portability limits its usage for resource-constrained devices compared to our solution. Since a trusted component like hypervisor must be verified in a critical system, the source code availability is important [36]. However, unlike iSotEE, both MultiZone and lLTZVisor are not open-source.

Apart from hypervisor, TEE (trusted execution environment) is another approach to enhance the reliability of IoT-enabled systems [37]. While a hypervisor mainly focuses on protecting the critical real-time tasks from the interferences of non-trusted applications, TEE ensures the confidentiality and integrity of data against possible attacks [38]. Typically, a TEE is not able to run a full-featured OS like a hypervisor, but can provide stronger isolation with its minimal attack surface. For resource-constrained devices using ARM processors, most TEEs are based on the hardware TrustZone feature [39]. Since hardware-based hypervisors on those devices also use TrustZone [35], they cannot coexist with TEE due to resource contention. iSotEE, as a software-based approach, is able to cooperate with TEE to further improve the reliability.

VII. CONCLUSION AND FUTURE WORK

We have introduced the iSotEE hypervisor middleware to provide a novel dual-OS solution for embedded systems. An IoT-enabled system based on iSotEE achieves high reliability and productivity, by using a reliable RTOS as the trusted host OS for critical applications and an IoT OS as the non-trusted guest OS for IoT applications. To support most resource-constrained devices, the generic design of iSotEE does not depend on special hardware features. Open-source implementations for Renesas RX and ARMv7-M architectures are provided and evaluated. The results show that a reliable system with iSotEE can meet resource constraints with a small footprint, guarantee real-time performance for critical applications, and deliver high throughput for IoT applications.

As future work, we plan to port iSotEE for more targets (e.g. mbed OS, RISC-V architecture) and extend the approach to multi-core devices. This paper mainly focused on reliability, but we believe iSotEE can be further improved to provide TEE (Trusted Execution Environment) for security.

REFERENCES

[1] M. Gaiceanu, "Cyber-physical systems for industrial applications," in *Proc. 6th Int. Symp. Electr. Electron. Eng. (ISEEE)*, Oct. 2019, pp. 1–3.
[2] N. Dey, A. S. Ashour, F. Shi, S. J. Fong, and J. M. R. Tavares, "Medical cyber-physical systems: A survey," *J. Med. Syst.*, vol. 42, no. 4, p. 74, 2018.
[3] C. Alcaraz and S. Zeadally, "Critical infrastructure protection: Requirements and challenges for the 21st century," *Int. J. Crit. Infrastruct. Protection*, vol. 8, pp. 53–66, Jan. 2015.
[4] V. Narayanan and Y. Xie, "Reliability concerns in embedded system designs," *Computer*, vol. 39, no. 1, pp. 118–120, 2006.
[5] M. Silva, D. Cerdeira, S. Pinto, and T. Gomes, "Operating systems for Internet of Things low-end devices: Analysis and benchmarking," *IEEE Internet Things J.*, vol. 6, no. 6, pp. 10375–10383, Dec. 2019.
[6] G. C. Buttazzo, *Hard Real-Time Computing Systems: Predictable Scheduling Algorithms and Applications*, vol. 24. New York, NY, USA: Springer, 2011.
[7] L. Wehmeyer and P. Marwedel, "Influence of memory hierarchies on predictability for time constrained embedded software," in *Proc. Design, Autom. Test Eur.*, Munich, Germany, 2005, pp. 600–605.
[8] S. S. Prabhu, H. Kapil, and S. H. Lakshmaiah, "Safety critical embedded software: Significance and approach to reliability," in *Proc. Int. Conf. Adv. Comput., Commun. Informat. (ICACCI)*, Bangalore, India, Sep. 2018, pp. 449–455.
[9] L. S. Azevedo, D. Parker, Y. Papadopoulos, M. Walker, I. Sorokos, and R. E. Araújo, "Exploring the impact of different cost heuristics in the allocation of safety integrity levels," in *Model-Based Safety and Assessment*. Munich, Germany: Springer, 2014, pp. 70–81.
[10] A. Burns and R. I. Davis, "A survey of research into mixed criticality systems," *ACM Comput. Surv.*, vol. 50, no. 6, pp. 1–37, Nov. 2018.
[11] A. Esper, G. Nelissen, V. Nélis, and E. Tovar, "An industrial view on the common academic understanding of mixed-criticality systems," *Real-Time Syst.*, vol. 54, no. 3, pp. 745–795, Jul. 2018.
[12] Y. B. Zikria, H. Yu, M. K. Afzal, M. H. Rehmani, and O. Hahm, "Internet of Things (IoT): Operating system, applications and protocols design, and validation techniques," *Future Gener. Comput. Syst.*, vol. 88, pp. 699–706, Nov. 2018.
[13] J. Wang, L. Zhang, L. Duan, and R. X. Gao, "A new paradigm of cloud-based predictive maintenance for intelligent manufacturing," *J. Intell. Manuf.*, vol. 28, no. 5, pp. 1125–1137, Mar. 2015.
[14] H.-N. Dai, H. Wang, G. Xu, J. Wan, and M. Imran, "Big data analytics for manufacturing Internet of Things: Opportunities, challenges and enabling technologies," *Enterprise Inf. Syst.*, vol. 14, nos. 9–10, pp. 1279–1303, Jun. 2019.
[15] K. Zandberg, K. Schleiser, F. Acosta, H. Tschofenig, and E. Baccelli, "Secure firmware updates for constrained IoT devices using open standards: A reality check," *IEEE Access*, vol. 7, pp. 71907–71920, 2019.
[16] A.-R. Sadeghi, C. Wachsmann, and M. Waidner, "Security and privacy challenges in industrial Internet of Things," in *Proc. 52nd Annu. Design Autom. Conf.*, San Francisco, CA, USA, Jun. 2015, p. 54.
[17] K. Parveen, A. Ali, and G. Asadullah, "Survey on operating systems for the applications of the Internet of Things," *J. Inf. Commun. Technol. Robot. Appl.*, vol. 7, no. 1, pp. 9–16, 2018.
[18] P. P. Ray, D. Dash, and D. De, "Edge computing for Internet of Things: A survey, e-healthcare case study and future direction," *J. Netw. Comput. Appl.*, vol. 140, pp. 1–22, Aug. 2019.
[19] O. Hahm, E. Baccelli, H. Petersen, and N. Tsiftes, "Operating systems for low-end devices in the Internet of Things: A survey," *IEEE Internet Things J.*, vol. 3, no. 5, pp. 720–734, Oct. 2016.
[20] S. Pinto and C. Garlati, "User mode interrupts: A must for securing embedded systems," in *Proc. Embedded World Conf.*, 2019, pp. 505–510.
[21] S. Pinto, H. Araujo, D. Oliveira, J. Martins, and A. Tavares, "Virtualization on TrustZone-enabled microcontrollers? Voilà!" in *Proc. IEEE Real-Time Embedded Technol. Appl. Symp. (RTAS)*, Apr. 2019.
[22] S. Pinto and N. Santos, "Demystifying arm TrustZone," *ACM Comput. Surv.*, vol. 51, no. 6, pp. 1–36, Nov. 2019.
[23] Y. Li, T. Ishikawa, Y. Matsubara, and H. Takada, "A platform for LEGO mindstorms EV3 based on an RTOS with MMU support," in *Proc. OSPERT*, 2014, pp. 51–59.
[24] F. Jaskani, S. Manzoor, M. Amin, M. Asif, and M. Irfan, "An investigation on several operating systems for Internet of Things," *EAI Endorsed Trans. Creative Technol.*, vol. 6, no. 18, Jan. 2019, Art. no. 160386.
[25] P. Kocher, J. Horn, A. Fogh, D. Genkin, D. Gruss, W. Haas, M. Hamburg, M. Lipp, S. Mangard, T. Prescher, M. Schwarz, and Y. Yarom, "Spectre attacks: Exploiting speculative execution," in *Proc. IEEE Symp. Secur. Privacy (SP)*, May 2019, pp. 1–19.
[26] Amazon Web Services. *FreeRTOS User Guide*. Accessed: Jan. 19, 2022. [Online]. Available: https://docs.aws.amazon.com/freertos/latest/userguide/freertos-ug.pdf
[27] J. Hiller, M. Henze, M. Serror, E. Wagner, J. N. Richter, and K. Wehrle, "Secure low latency communication for constrained industrial IoT scenarios," in *Proc. IEEE 43rd Conf. Local Comput. Netw. (LCN)*, Oct. 2018, pp. 614–622.
[28] W. Lamie and J. Carbone, "Measure your RTOS's real-time performance," *Embedded Syst. Des.*, vol. 20, no. 5, pp. 44–54, 2007.
[29] A. Madhavapeddy, R. Mortier, C. Rotsos, D. Scott, B. Singh, T. Gazagnaire, S. Smith, S. Hand, and J. Crowcroft, "Unikernels: Library operating systems for the cloud," *ACM SIGARCH Comput. Archit. News*, vol. 41, no. 1, pp. 461–472, 2013.
[30] M. Cinque, D. Cotroneo, L. De Simone, and S. Rosiello, "Virtualizing mixed-criticality systems: A survey on industrial trends and issues," *Future Gener. Comput. Syst.*, vol. 129, pp. 315–330, Apr. 2022.
[31] H. Li, X. Xu, J. Ren, and Y. Dong, "ACRN: A big little hypervisor for IoT development," in *Proc. 15th ACM SIGPLAN/SIGOPS Int. Conf. Virtual Execution Environ.* New York, NY, USA: ACM Press, 2019, pp. 31–44.
[32] J. Martins, A. Tavares, M. Solieri, M. Bertogna, and S. Pinto, "Bao: A lightweight static partitioning hypervisor for modern multi-core embedded systems," in *Proc. Workshop Next Gener. Real-Time Embedded Syst.*, 2020, pp. 3:1–3:14.
[33] Project ACRN. (2021). *ACRN Hypervisor Release Version 2.6*. [Online]. Available: https://projectacrn.org/acrn-hypervisor-release-version-2-6/
[34] C. Garlati, "Configuring, enforcing, and monitoring separation of trusted execution environments," U.S. Patent 11 151 262 B2, Oct. 19, 2021.
[35] A. M. M. D. Santos, "Towards multi-OS support on TrustZone-M MCUs," M.S. thesis, Dept. Ind. Electron., Univ. Minho, Braga, Portugal, 2020.
[36] D. Lee, D. Kohlbrenner, S. Shinde, K. Asanović, and D. Song, "Keystone: An open framework for architecting trusted execution environments," in *Proc. 15th Eur. Conf. Comput. Syst.*, Apr. 2020, pp. 1–16.
[37] D. Valadares, N. Will, M. Spohn, D. Santos, A. Perkusich, and K. Gorgonio, "Trusted execution environments for cloud/fog-based Internet of Things applications," in *Proc. 11th Int. Conf. Cloud Comput. Services Sci.*, Setúbal, Portugal, 2021, pp. 111–121.
[38] L. Luo, Y. Zhang, C. Zou, X. Shao, Z. Ling, and X. Fu, "On runtime software security of TrustZone-M based IoT devices," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2020, pp. 1–7.
[39] N. Koutroumpouchos, C. Ntantogian, and C. Xenakis, "Building trust for smart connected devices: The challenges and pitfalls of TrustZone," *Sensors*, vol. 21, no. 2, p. 520, Jan. 2021.

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