Poster: μRAI: Securing Embedded Systems with Return Address Integrity

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Abstract

Embedded systems are deployed in security critical environments and have become a prominent target for remote attacks. Microcontroller-based systems (MCUS) are particularly vulnerable due to a combination of limited resources and low level programming which leads to bugs. Since MCUS are often a part of larger systems, vulnerabilities may jeopardize not just the security of the device itself but that of other systems as well. For example, exploiting a WiFi System on Chip (SoC) allows an attacker to hijack the smart phone's application processor.

Control-flow hijacking targeting the backward edge (e.g., Return-Oriented Programming–ROP) remains a threat for MCUS. Current defenses are either susceptible to ROP-style attacks or require special hardware such as a Trusted Execution Environment (TEE) that is not commonly available on MCUS.

We present μRAI [1], a compiler-based mitigation to *prevent* control-flow hijacking attacks targeting backward edges by enforcing the *Return Address Integrity (RAI)* property on MCUS. μRAI does not require any additional hardware such as TEE, making it applicable to the wide majority of MCUS. To achieve this, μRAI introduces a technique that moves return addresses from writable memory, to readable and executable memory. It re-purposes a single general purpose register that is never spilled, and uses it to resolve the correct return location. We evaluate against the different control-flow hijacking attacks scenarios targeting return addresses (e.g., arbitrary write), and demonstrate how μRAI prevents them all. Moreover, our evaluation shows that μRAI enforces its protection with negligible overhead.

1 Reference

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[1] https://github.com/embedded-sec/uRAI

µRAI : Securing Embedded Systems with Return Address Integrity[1]

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Problem

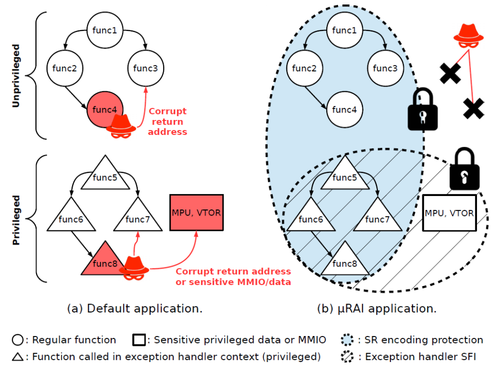
- **Embedded systems** and **IoT** are run on Microcontroller systems (**MCUS**)
- **MCUS** lack basic mitigations and are **prone to control-flow hijacking attacks** such as Return Oriented Programming (**ROP**)
- Proposed defenses have limited security guarantees, high runtime overhead, or require special hardware features

Objectives

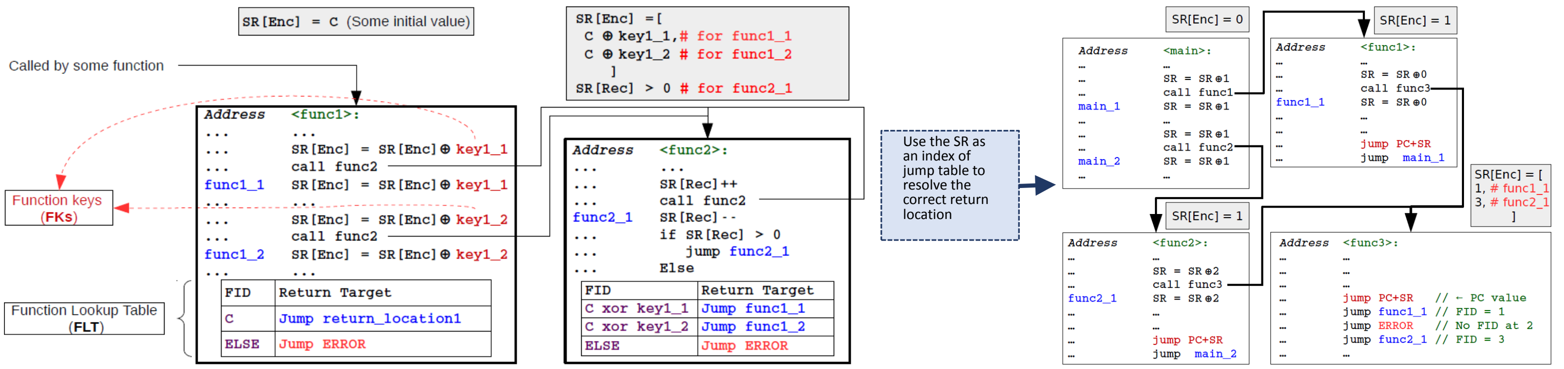
- Return Address Integrity (**RAI**) prevents ROP attacks on MCUS
- RAI results in **low runtime overhead**
- RAI **does not require** special hardware

µRAI

- Identifies the possible return targets of each function in the call graph
- Transforms the set of return targets to a jump table in R+X memory
- Introduces a State Register (**SR**), which is **never spilled** and is exclusively used by µRAI
- Uses the SR at run time to resolve the correct return location from the jump table
- **Enforces the RAI property** since the SR and jump table are **inaccessible** to an adversary
- Protects sensitive Memory Mapped IO (MMIO) by enforcing Software-based Fault Isolation (SFI) on functions callable within an exception handler context to protect sensitive such as the MPU
- Partitions the SR into segments to curb path explosion
- Applies a type-based CFI for forward edges

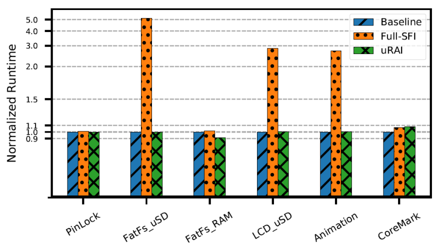


Compiler Transformation



Evaluation

Runtime



µRAI enforces the RAI property with low overhead in contrast to mechanisms requiring full-SFI

Comparison to backward edge Type-based CFI

App	Type-based CFI Target Set Max.	Type-based CFI Target Set Ave.
PinLock	8	3
FatFs_uSD	94	21
FatFs_RAM	94	27
LCD_uSD	49	11
Animation	49	11
CoreMark	52	12

µRAI eliminates the remaining attack surface for control-flow bending attacks

Security

Attack	Prevented
Buffer overflow	✓
Arbitrary write	✓
Stack pivot	✓

µRAI prevents all control-flow hijacking attack scenarios targeting return addresses

References

[1] Naif Saleh Almakhdhub, Abraham A Clements, Saurabh Bagchi, and Mathias Payer. In *The Annual Network and Distributed System Security Symposium* (**NDSS**), ***2020***

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