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Hardware-Based Security for Embedded Systems: It is protection against modern threats

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Abstract

Our daily lives are becoming increasingly reliant on embedded systems, for which advancements in technology seem to progress with a degree of 'news almost every day'. Regardless of whether this computer system is in smartphones and smart home devices or in industrial control systems and automotive electronics this computer system is everywhere. However, as they become more comfortable with the current, more and more demands are being requested from robust security measures to protect against evolving cyber threats. The past decade has seen dramatic changes in what is involved in building a secure embedded systems. Embedded devices were deployed pretty much in isolation and thus had little interaction with other devices, and consequently, were not in the line of fire for external threats. Until the advent of the Internet of Things (IoT), this paradigm remained the status quo, but that has completely changed. Today's embedded systems are located in communication with large numbers of other devices, not only are interconnect, but they share data. This new connectivity greatly enhanced functionality (because the networking had been much improved), but it also presented new ways to attack.

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Introduction

The embedded system security challenges are unique and spread widely. On the other hand, resource constraint very different from those facing current IT systems (e.g., due to memory, power, or processing constraint) embedding devices. This is why, to implement comprehensive software based security solutions, it becomes hard. Also, most embedded systems can live its life for decades, where its security is obsolete. In view of these challenges, hardware based security solutions for embedded systems have become popular. A robust foundation of the system security is used to be based on features and hardware components dedicated for security. Security measures embedded at the hardware level would benefit the embedded system to have a higher level of protection from modern threats and in low resources environment.[1-3]

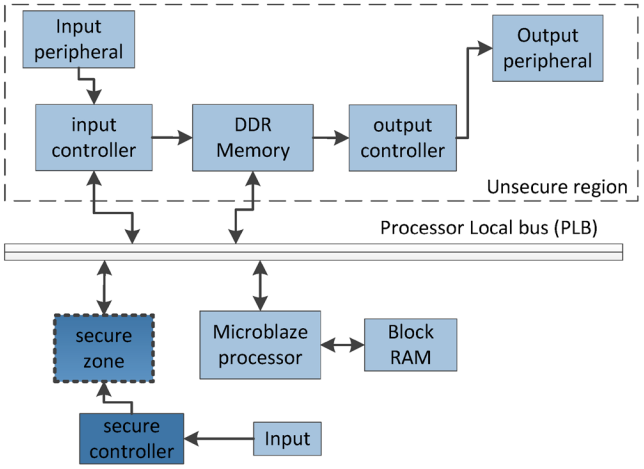

Fig. 1: Hardware Based Security

Hardware Based Security

Specialized hardware components or features used to enhance a systems security are hardware security. From this point of view, we have a number of advantages

of purely software solutions. Hardware based security also includes secure boot. The advantage here is that the system does not load the allowed and original software only when it initiates the Boot process. This is used to verify the integrity of the boot code and the processes coming after it so that it prevents the malware from infecting in the system and also modifications are not allowed in the system.

Furthermore, the hardware based security also enables the use of TEEs. It means these are the small isolated area of the processor so that we can operate sensitive operations and store sensitive data on this isolated area. A feature of TEEs is that they protect against software based attacks and they can have features such as secure key storage and a secure channels for communication. Another important key aspect of hardware based security is Hardware Security for Embedded Systems which uses Hardware Security Modules (HSM). Cryptographic devices for use in dedicated secure environments where cryptographic operations can be carried out and cryptographic keys can be stored in a secure manner are offered. HSMs are used in high security applications.[4-5]

Hardware Based Security Key Components

An essential aspect of security for such embedded systems is to have a proper architecture of security from all components working together. Here are some of the most important among them. The goal is to create tamper resistant hardware components that are referred to as secure elements to hold sensitive information securely and perform crypto operations. Storage of cryptographic keys and certificates safely into our private cloud (Table1).

Once the system was initialized by the ROM code, they loads the bootloader from the non volatile storage. There is checking the version of the bootloader to prevent downgrade attacks, verifying the bootloader's digital signature by use of a public key stored in secure memory, and verifying that the bootloader image has not been modified.tem, the bootloader is loaded from nonvolatile storage. The ROM code does a number of security checks before running the bootloader. Checking the digital signature of the bootloader with a stored electronic public key within the secure memory.[6-7]]

On any type of failure of these checks, the boot process halts and stops running potentially malicious code. Finally, the bootloader is then the beginning of the trust chain, which continues to verified and executed, verifying the operating system, as well as other critical applications one by one. Testing of digital signatures for OS components and applications Trying to perform digital signatures on OS components and applications Testing of integrity of filesystem images. The bootloader then loads all loaded components into the system's security policy requirements.

Table 1: Hardware Security for Embedded Systems

Challenge	Description	Impact
Limited Computational Resources	Embedded systems often have constrained memory, processing power, and energy resources, making implementing complex security protocols difficult.	Constrained resources limit the deployment of sophisticated security measures, leaving systems vulnerable.
Physical Tampering Risks	Hardware-based security solutions are susceptible to physical attacks such as reverse engineering and tampering with the device.	Tampering may compromise the integrity of security features, rendering the system unreliable.
Vulnerability to Side-Channel Attacks	Side-channel attacks exploit unintended information leaks from embedded systems, such as power consumption or electromagnetic radiation.	Side-channel attacks can expose sensitive data or system keys, undermining the security of the embedded device.
Software-Hardware Integration Issues	Ensuring seamless integration between hardware security modules and embedded software can be a complex and error-prone task.	Poor integration between hardware and software security can lead to system vulnerabilities or performance bottlenecks.

The ROM code does several security checks before executing the bootloader. Upon the verification and execution of the bootloader, it continues the chain of trust to verify the operating system kernel and any critical applications. This process typically involves. It performs checking of digital signatures on OS components and applications. Verifying the integrity of filesystem image and validating the results of its filesystem checking programs. Regardless of its components, the system should ensure in the within the entire application that it has a complete set of overall security policy requirements. Secure boot provides an overall assurance that the embedded system is in fact in a good state through maintaining the chain of trust from the hardware root of trust past the software root of trust, even to the root of trust in the installed IO firmware.[8-9]

Challenges and Considerations

There are some challenges that have to be taken care of while implementing secure boot in embedded systems: Performance impact: If the startup time of the system has to meet rigid timeliness requirements, signature verification and integrity checks may be too boot time expensive. Beyond introducing security flaws in boot processes, think of introducing security flaws in domains, data centers, workstations, in system integrity management, and data confidentiality, including key management with your cryptographic keys. The design of a secure method to update bootloader and OS components is required so that it does not break the secure boot process. Secure recovery procedures must be introduced for local recovery in case of verification failures or for system updates not functioning correctly for the system to be resilient.

However, these challenges are solved by thoughtful design and implementation and judicious combination of hardware and software solutions specifically designed to satisfy those of embedded systems.[10]-[11]

Trusted Execution Environments (TEEs) embedded systems

The term Trust Execution Environments (TEEs) refer to secure, isolated area within a processor for executing sensitive code or storing critical data. TEEs are a very powerful way of getting increased security with minimal dedicated security hardware for some cases. Here, we are going to uncover the principal aspects of TEEs on embedded systems.

Architecture of TEEs

In this part, sensitivevoke operations are being performed as per isolation. It has its own memory, storage (and hopefully its own operating system). This is the normal operating environment, the main operating system and all course run in this execution environment. However, these two worlds are separated at processor hardware living side, normal world processes can no longer access Code and Data in the Secure World. However, these two worlds are separated at processor hardware living side, normal world processes can no longer access Code and Data in the Secure World.[12]

Hardware assisted Cryptography

Another issue to be considered when integration of hardware–assisted cryptography into embedded systems is, algorithm Support: Be sure that the chosen hardware has the ability to run the crypto algorithms and key sizes that you want to use in your application. Performance needs: The performance requirements of your system needs to be evaluated and you have to choose hardware that meets the performance requirements along with suits its power and cost bounds. It provides secure key generation mechanism, storage mechanism and management mechanism of key; if hardware secured storage is available, that can be used as storage base. Efficiently integrate software libraries as the application developers use these libraries to bridge the application details from the low level. Security Certification: If you require that you will have high assurance, you may choose to use cryptographic hardware which has already been security certified, such as FIPS 140-2. On the other hand, with a judicious choice and use of hardware supported cryptography solutions, the embedded system developer in a very appreciable manner can enhance the security and performance of his embedded system to the environment in which the system is being developed in resource constrained environment (Figure 2).[13]

Embedded Systems Secure Storage Solutions

Vital importance is the security of the system, which also means the security, and respectively, the privacy of the data that is stored on embedded devices. Secure storage solutions provided with use of the hardware are extremely resilient against physical and soft software attacks. The key aspects to implement secure storage in embedded systems are:

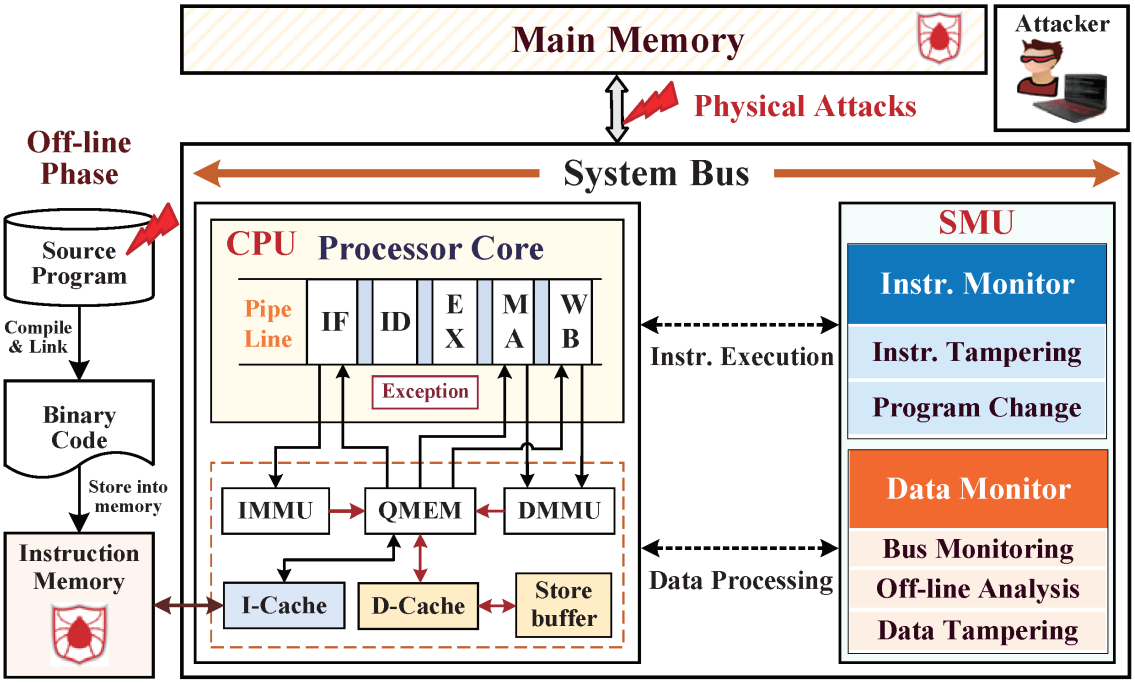

Fig. 2: Embedded Systems Secure Storage

Types of Secure Storage

Among embedded systems to implement the secure storage, there are available several hardware based options.

1. **These Secure Elements:** they are dedicated chips with tamper resistant storage of small amounts of sensitive data such as cryptographic keys and device identities.
2. Security chips often used for secure storage functions (as well as other cryptographic functions) Known as Trusted Platform Modules (TPMs).
3. Secure Storage in 3. eMMC and UFS: There are secure storage regions within specific embedded storage solutions based on hardware which can be used for protecting sensitive data.
4. Many modern processors (e.g., secure enclaves or trusted execution environments) can be used to achieve secure storage.

Secure Storage Solutions Key Features

Typically, an effective implementation of secure storage for embedded system includes the following features. Encrypting it before storing it in the secured storage will help defend against unauthorized access. Robust mechanisms should deal with Control & authentication of access to the secure storage areas. An issue to be detected and responded to by physical security measures is that of tamper resistance, i.e. the detection of tampering attempts and locking down of tampering attempts. Secure Key Management: The other option for securing the storage of your cryptographic keys is to also secure the key with cryptographic keys; this is generally done in what's called hardware key storage. Integrity Protection: A set of mechanisms for uncovering unauthorized data modification in stored data.[14-15]

Secure Storage in Embedded Systems

Determine how you want to assess your security requirements. This would help you determine the level of security necessary for different types of data in your system and assist you to find the right solution to store them. Use Hardware Security Wherever Possible: At least try your hard to use hardware based secure storage as it is going to be more secure than other alternatives. Use Defense in Depth: Conspicuously select more than one security measures such as encryption, access control and integrity check then join these security features to put a layered defense. Performance Impact: Balance the requirement of security with system performance requirement: Compenstate the cost of accessing secure storage by adding latency. Key Management: Plan for how to deal with cryptographic keys used in secure storage for the rest of life_circle as full suite of strategies including

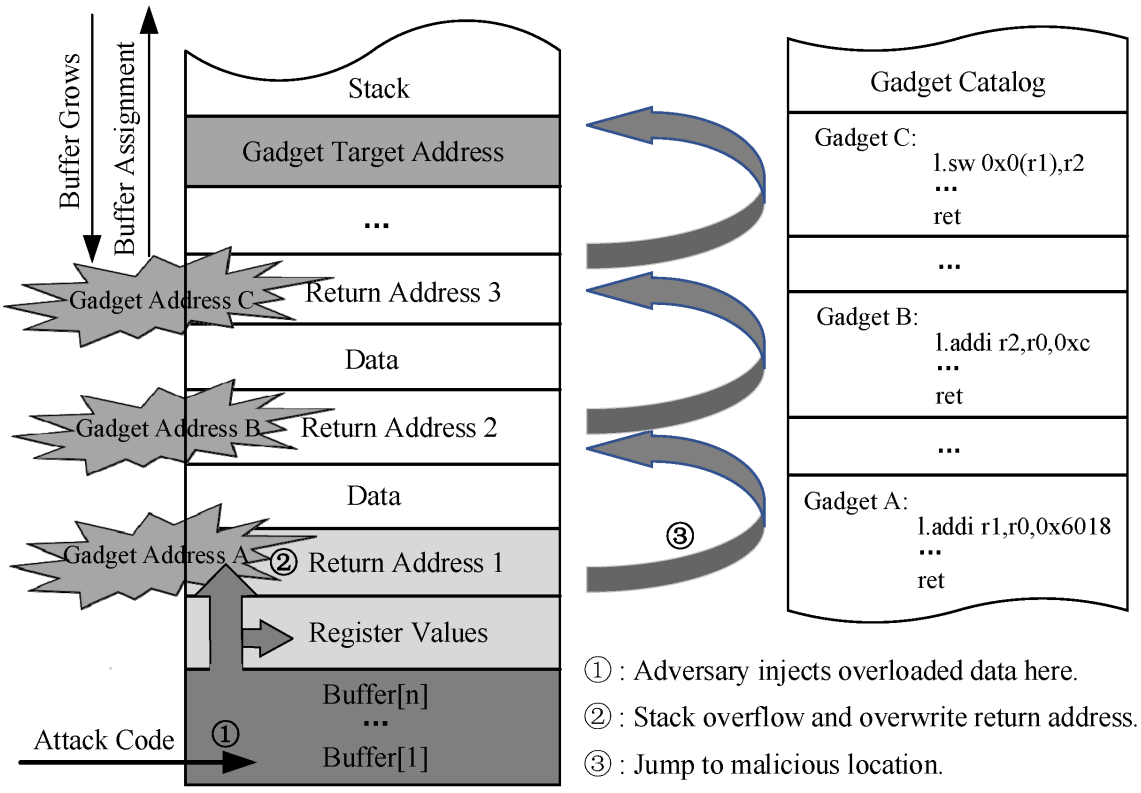

Fig. 3: Hardware Based Isolation, Virtualization

key generation, key distribution and even key rotation. Provide mechanisms to securely update stored data as well as associated security parameters when they need to be updated. By exercising safe use of secure storage solutions on embedded systems, developers can vastly enhance the protection of sensitive data despite the possibility of running in an untrusting environment (Figure 3).[16]-[19]

Hardware Based Isolation, Virtualization

This thesis has researched hardware based isolation and virtualization techniques for raising the security of embedded systems. In both cases, these approaches utilize the CPU features to establish secure execution environments that prevent the critical components from being attacked. We will now examine the main characteristics of hardware isolation and virtualization in embedded system.

Hardware Based isolation Types

There are a number of hardware based isolation techniques applicable to embedded systems. Memory Protection Units (MPUs): The way they break memory into specific areas and demand that application components respect the access controls of these areas is very valuable, and we reserve access between the different application components from those that are unauthorized. Virtualization Extensions: Today, many modern processors support virtualization, with added hardware support for that purpose via virtual machines. TrustZone Technology: ARM's TrustZone provides hardware based separation of secure to non secure areas of execution. This technology intel software guard extensions (SGX): The idea of this technology is to segregate sensitive code and data, the enclaves act like something which segregates the code within an application keeping the rest of the application and also segregate the data in such a secure way.[20-21]

Benefits of Hardware Based Isolation

Some advantages of implementing hardware based isolation are: It decreased the attack surface by separating the critical components from the non trusted parts of the system. Isolation simplifies the security certification of security critical parts since it also removes dependence on other parts of a system. Virtualization can help in a legacy code support in a

secure manner, by bringing security enhanced modern components with legacy code. To Provide Resource Partitioning: Hardware isolation may be used to enforce strict resource allocation between a system component to protect against denial of service attacks inside the system.

Hardware Based Isolation in Embedded Systems

Best practices for integrating a hardware based isolation functionality into embedded systems include: By taking advantage of hardware isolation techniques and leveraging virtualization, embedded system designers can create more resilient and, as a result more secure, architectures based on the complex and interconnected environments they inhabit. Keeping the security of one of today's most important current aspect of embedded systems: it is the security of their channel of communication. Very powerful tools to increase embedded system's IPC communications security can be provided by hardware based solutions. The next thing is to see how one can implement secure communication in an embedded system.[22-23]

Hardware helps in assisting Secure Communication Protocols.

Securing communications in embedded systems may be achieved using several hardware assisted protocols and technologies.

1. **Transport Layer Security (TLS) with Hardware Acceleration:** Today this is not true and there are many modern processors with hardware acceleration of TLS in hardware to speed up computation and reduce power consumption.
2. **Hardware Offload for IPsec:** IPsec has hardware support on some network interfaces, and constitutes almost no CPU overhead in the IPsec networking.
3. **Bluetooth Low Energy (BLE) with Link Layer Encryption:** The short range wireless communications most commonly support Link Layer Encryption with the help of hardware in order to connect with the base system of the BLE implementation thus providing a decent level of security.
4. On the LoRaWAN module side, they actually have certain LoRaWAN modules which are bundled with internal security services including embedded secure element for key storage and management.

Best practices for integrating secure communication solutions into embedded systems are as follows: By employing secure communication techniques in the design of embedded systems one can add, significantly, to the amount of protection afforded to data in transit in potentially hostile network environments. Hardware based anomaly detection and intrusion prevention is becoming a necessity for a complete security strategy, because the threats on ever more sophisticated embedded systems are ever more sophisticated. Based on this dedicated hardware, these technologies are able to accurately measure system behavior and can detect breaches to security in real time. In this post, I would like to discuss the major aspects involved during hardware based anomaly detection and intrusion prevention in embedded systems (Table 2) [24]

Table 2: Security solutions and their benefits to address challenges

Solution	Description	Benefit
Hardware Security Modules (HSM)	Dedicated hardware modules designed to securely store cryptographic keys and protect sensitive operations.	Provides a high level of protection for sensitive data, reducing risks of key exposure and unauthorized access.
Trusted Execution Environments (TEE)	Isolated execution environments that ensure critical processes run securely, even in the presence of untrusted software.	Enhances system security by isolating sensitive operations from potential threats in the rest of the system.
Secure Boot Mechanisms	A security mechanism that ensures only trusted software can run on the system by verifying its integrity at boot time.	Prevents unauthorized software from compromising the system, ensuring only verified code is executed.
Side-Channel Resistance Techniques	Techniques such as power analysis resistance, electromagnetic shielding, and noise injection to prevent side-channel attacks.	Protects against side-channel attacks, which could otherwise compromise system security through subtle leaks of information.

Hardware Based Security Future Trends for Embedded Systems

As a result, the landscape of embedded systems has evolved into the current landscape and hardware based security field also has been added. Emerging technologies, changing threat landscape are driving new ways to protect embedded devices. Now let's dig into some of the high level trends that hardware based security for embedded systems will be based on going forward.

The integration of such AI and machine learning capabilities into the realm of hardware security solutions is a growing trend. Security Breach – AI powered hardware can monitor more accurately for odd behavior of the system which may be a sign of a security breach. Security systems, on the other hand, have their own set of adaptive security that is based on machine learning algorithms that it can learn and adapt to new threats in real time. Less performance overhead, a more sophisticated security analysis is possible at the cost of additional hardware resources if dedicated AI processors are used.[25]

Quantum resistant Cryptography

Today, as quantum computing continues to make great strides, the need for such cryptographic systems increases as quantum computers make attacks against them easier and easier. Problem of developing new cryptographic algorithms which are quantum resistant, i.e. post-Quantum Algorithms. A hardware-based security using blockchain and related technologies for embedded systems applications are also being realized. Tamper Resilient Tokens using Blockchain: Create tamper resilient tokens out of devices and/or their identities. As embedded systems become more and more interconnected and proliferate, hardware based security becomes more and more important. This is a field changing very fast, developers and system designers should attempt not to fall far behind the new, never was yet technology and not immediately utilize them into a product. By doing that they can create more resilient, trustable and secure embedded system that can be alive there in the threat landscape of our increasingly connected world.

Embedded systems hardware based security is clearly what to do and it is bright keeping in mind the fact that even beyond PUF technologies application of AI based security and quantum resistant cryptography lead hints towards more secured embedded systems. These technologies will continue to mature and be adopted and we should see the emergence of new generations of embedded systems that are inherently more secure, more reliable and capable of protecting the critical functions and sensitive data they process. Finally, unlike the case of adding some software based security on top of the basic software of an embedded system, the hardware based security is not a feature that can be simply added to an embedded system. Indeed, this is a key aspect of building trust in our digital infrastructures. If embedded systems developers take a look at these technologies and this best practices, we can have some safer future embedded systems in all industries and applications.

Conclusion

However, while awkward devices, more advanced cyber attacks, and updated regulation on the use of embedded system security are advancing the rate of change in the field of hardware based security for embedded systems, the idea of hardware based security is simple and natural. But then, as we said in this article, there are various attacks and their vectors that are compensated by performance, power efficiency and security posture at all the means than purely software based solutions. As secure embedded systems require an additional layer of protection, security features at the hardware level are becoming an essential part of building such system, with: secure boot mechanisms, trusted execution environments, hardware assisted cryptography and anomaly detection. Moreover, these technologies are not only defensive to the security threats of the present environment but also provide a platform for the further enhancement of security issues.

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