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Trends in Software Development for Embedded Systems in Cyber-Physical Systems

L. Parizi[1], J. Dobrigkeit[2], K. Wirth[3]*

[1-3]Department of Computer Science, UIUC, USA

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Corresponding Author Email:
wirthk@illinois.edu

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Abstract

Current landscape for embedded systems is gradually shifting due to developments and trends in Cyber Physical Systems and Internet of Things (IoT). In the overall march into the year 2024 and beyond, software development for embedded systems is shifting in a direction that will suit the new world of interconnectivity and smart devices. This article covers the most exciting trends in today's embedded systems and the directions where the future development of the sphere lies: from new types of security as the basis of modern systems to the progressive architecture and electronics. Currently, the overall embedded systems market in the world has a very high growth rate; according to the forecasts, it will increase from 91.95 billion USD in 2024 to 124.80 billion USD by 2029, CAGR 6.3 %. This expansion demonstrates how importance is the place of the embedded systems application in healthcare, automotive, industrial automation, and consumer electronics industries. With the advancement and advancement of those systems, there are new problems and prospects in building more resilient and dependable solutions. In the next few sections, we will be seeing how these and other trends are changing the embedded systems development, discussing methodology, hardware issues and software implications. These trends are quite existing in the future development of embedded systems in cyber-physical systems involving artificial intelligence, use of machine learning, connectivity technologies, and cybersecurity.

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Edge AI and Machine Learning Narinder Singh zipfile

AI and specifically, ML take embedded systems to an even higher level, as they become a part of the system. Edge AI that is the complement to the concept of moving computing closer to the source of data impacts how embedded systems approach information processing and reaction.

Decision Making for the Internet of Things - Performance Improvement Edge AI allows for decision-making at the edge while disconnected from cloud connections, thus cutting latency and promoting privacy. This capability is especially important in areas like self-driving cars, industrial automation, as well as the IoT-based healthcare tools where a decision usually needs to be made in a blink of an eye. For example, in the manufacturing context, the AI-based cameras interpret and identify defects that can be corrected on the spot without having to transfer the data to the main server for analysis. This not only optimizes performance but also offloads a chunk of load on the networks and overall system plus boosts the general response time.

The last class is concerned with the efficient and effective use of resources available in order to achieve good results.[1-5]

One of the most significant issues of deploying ML algorithms in embedded systems is that there are various and strict constrains in resources and power. They are recently paying efforts to building light weight ML models and using techniques like hardware acceleration for faster processing while maintaining energy costs low. These form the approaches in model compression, quantization, and pruning leading to miniaturized models suitable for implementation in understaffed devices. This optimization makes it possible to have smart AI enhancements in devices with relatively small footprints increasing the horizon of applications of intelligent embedded systems.[6-8]

Adaptive Systems and Life Cycle Predictive Maintenance.

Other functions are allowing outcomes of the computations performed by the embedded systems to be adjusted on the basis of changing conditions, an aspect that allows problems to be anticipated even before they manifest themselves. In industries, the use of machine learning based IoT predictive maintenance can be used to predict equipment failures based on sensor data to reduce the amount of time an equipment is out of service. This trends to Adaptive and predictive systems are not monopoly of industrial applications. Gizmos and gadgets, for example, smart home appliances, use Algorithms to learn from the consumer the most preferred settings that would enhance energy efficiency and further enhance the user experience.[9-10]

Cybersecurity Implementations in Embedded Systems

Since more complex and safer systems are being incorporated in smart devices and core infrastructures, therefore, enhancing the security feature is now a paramount necessity. The improvement of the recent regulation and the increase in the recognition of cyber risks are the main factors in the development of embedded system security.

The authors have discussed Regulatory Landscape and Compliance thus:

Cybersecurity requirements, like the new U.S. Executive Order 14028 and FDA guidelines for protecting medical devices and their networks, is now driving the redesign of security in embedded systems. These regulations call for full-fledged security solutions at the product development phase and at the phase of offering support services to the product that is in use. Having organized boot mechanisms through security processes to assure the firmware integrity • Implementation of encryption methods/methodology. Technologies Multiple objects:

- Using secure channel techniques• Establishing strong update processes for handling of the same
- Creating the continuous monitoring and the procedures of handling the incidents.

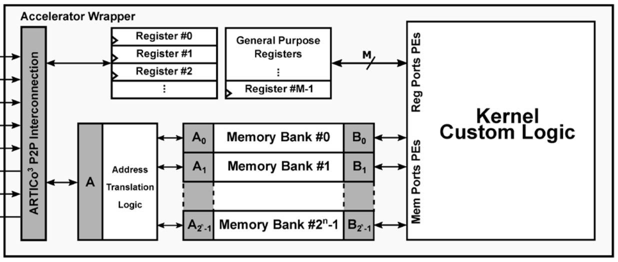

Fig. 1: Cybersecurity Implementations in Embedded Systems

The landscape of embedded systems is undergoing a profound transformation, driven by the rapid evolution of cyber-physical systems and the Internet of Things (IoT). As we venture into 2024 and beyond, software development for embedded systems is adapting to meet the demands of an increasingly interconnected and intelligent world. This article explores the cutting-edge trends shaping the future of embedded systems development, from advanced security measures to innovative architectures and technologies. The global embedded systems market is experiencing remarkable growth, with projections indicating a surge from $91.95 billion in 2024 to $124.80 billion by 2029, at a compound annual growth rate (CAGR) of 6.3%. This expansion underscores the critical role embedded systems play across various sectors, including healthcare, automotive, industrial automation, and consumer electronics. As these systems become more sophisticated and interconnected, developers face new challenges and opportunities in creating robust, efficient, and secure solutions.

In the following sections, we'll delve into the key trends that are revolutionizing embedded systems development, examining their impact on design methodologies, hardware integration, and software architectures. From the integration of artificial intelligence and machine learning to the adoption of new connectivity technologies and cybersecurity measures, these trends are shaping the future of embedded systems in cyber-physical environments.

The Rise of Edge AI and Machine Learning. The integration of artificial intelligence (AI) and machine learning (ML) into embedded systems marks a significant leap forward in their capabilities. Edge AI, which brings computational intelligence closer to the data source, is transforming how embedded systems process and respond to information in real-time.[11-13]

Enhancing Decision-Making at the Edge

Edge AI enables embedded systems to make intelligent decisions without relying on cloud connectivity, reducing latency and enhancing privacy. This capability is particularly crucial in applications such as autonomous vehicles, industrial robotics, and smart healthcare devices, where split-second decisions can be critical. For instance, in manufacturing environments, AI-enabled cameras can detect defects in real-time, allowing for immediate corrective actions without the need to send data to a centralized server for analysis. This not only improves efficiency but also reduces the strain on network resources and enhances overall system responsiveness.

Optimizing Resource Utilization

The implementation of ML algorithms in embedded systems presents unique challenges due to limited computational resources and power constraints. Developers are focusing on creating lightweight ML models and utilizing hardware acceleration techniques to optimize performance without compromising energy efficiency. Techniques such as model compression, quantization, and pruning are being employed to reduce the size and computational requirements of ML models, making them suitable for deployment on resource-constrained embedded devices. This optimization allows for the integration of sophisticated AI capabilities even in small form-factor devices, expanding the potential applications of intelligent embedded systems.

Adaptive Systems and Predictive Maintenance

Machine learning algorithms are enabling embedded systems to adapt to changing conditions and predict potential issues before they occur. In industrial settings, ML-powered predictive maintenance systems can analyze sensor data to forecast equipment failures, allowing for proactive maintenance and minimizing downtime. This trend towards adaptive and predictive systems is not limited to industrial applications. Consumer devices, such as smart home appliances, are increasingly incorporating ML algorithms to learn user preferences and optimize their operation, leading to improved energy efficiency and user experience.

Cybersecurity Imperatives in Embedded Systems

As embedded systems become more connected and integral to critical infrastructure, the importance of robust cybersecurity measures has never been greater. Recent regulatory changes and growing awareness of cyber threats are driving significant developments in embedded system security.

Regulatory Landscape and Compliance

New cybersecurity mandates, such as the U.S. Executive Order 14028 and FDA guidance for medical devices, are reshaping the approach to security in embedded systems development. These regulations require manufacturers to implement comprehensive security measures throughout the product lifecycle, from design to post-deployment support. Applying ‘security by design’ becomes nearly essential to developing next generation connected embedded systems. This approach is centered on attempting to incorporate design considerations of security right from the design phase as opposed to an addition phase. • Risk assessment to determine the type of risks that can be experienced • Appointing the concept of least privilege in system design• Employing of hardware based security components including trusted platform modules (TPMs)• Providing for capability for secure update and for remote management.

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The landscape of embedded systems is undergoing a profound transformation, driven by the rapid evolution of cyber-physical systems and the Internet of Things (IoT). As we venture into 2024 and beyond, software development for embedded systems is adapting to meet the demands

Table 1: Software Development Trends for Embedded Cyber-Physical Systems

Trend	Focus
Model-Driven Development	Model-driven development focuses on creating abstract models of embedded systems, improving design accuracy and reducing development time.
Agile Methodologies	Agile methodologies promote iterative development, allowing teams to deliver continuous improvements and adapt to evolving system requirements.
DevOps Practices	DevOps practices integrate development and operations, facilitating faster deployment and continuous integration of software for embedded systems.
Microservices Architecture	Microservices architecture decomposes software into smaller, loosely coupled services, enhancing modularity, scalability, and maintainability in embedded systems.
Real-Time Operating Systems	Real-time operating systems (RTOS) provide deterministic behavior, crucial for cyber-physical systems with strict timing and synchronization requirements.
Automated Testing	Automated testing allows for continuous validation of embedded systems, reducing human error and speeding up development cycles.

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Compliance with these mandates necessitates a shift in development practices, including:

The growth in IoT and cyber-physical systems is introducing several new connectivity technologies that will address the varying demands of the embedded systems in use today. New opportunities are arising from the implementation of the 5G networks for the embedded systems since it provides seamless connectivity at high speed, low latency. The roles expected to be solved by the 5G technologies as it grows include the applications like auto mobiles, smart cities and industrial IOT.• THz frequency communication for UHB• Of the nine research themes, the most relevant to the future network vision is Integration with AI for intelligent network.

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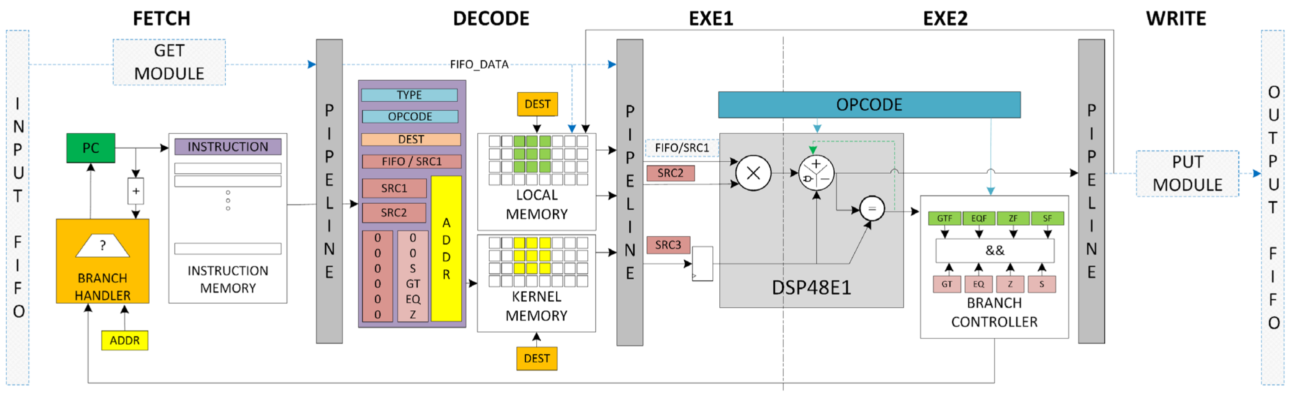

Fig. 2: Cybersecurity Imperatives in Embedded Systems

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Table 2: Approaches for Software Optimization in Embedded Systems

Approach	Goal
Memory Optimization	Memory optimization techniques ensure that embedded systems make the most efficient use of limited memory resources, crucial for resource-constrained environments.
Energy Efficiency	Energy efficiency strategies reduce power consumption in embedded systems, extending battery life and making systems more sustainable.
Parallel Computing	Parallel computing techniques enable faster processing by distributing tasks across multiple cores or processors in embedded systems.
Fault Tolerance	Fault tolerance techniques ensure the system remains operational even in the event of hardware or software failures, maintaining system reliability.
Real-Time Performance	Real-time performance guarantees that the embedded system can meet stringent timing constraints, ensuring responsive and predictable behavior in critical applications.
Code Minimization	Code minimization reduces the size of software code, optimizing it for resource-constrained embedded systems while maintaining functionality.

Low Power Wide Area Networks (LPWAN)

For long-range transmission in large, extended areas with low power consumption, low power wide area networks LPWAN are emerging especially LoRaWAN and NB-IoT. Such technologies are applied best in areas such as pollution or climate change detection, agricultural activities, and tracking of assets.• Better battery health for infrequent and difficult to charge gadgets• The deployment of the advertising is relatively inexpensive, especially across large regions.• Basic reference model that can support huge amount of connectivity of devicesat require long-range communication with minimal power consumption, LPWAN technologies like LoRaWAN and NB-IoT are gaining traction. These technologies are particularly well-suited for applications such as environmental monitoring, smart agriculture, and asset tracking.[19]

New protocol is introduced in the short range communication area as to meet the requirement for the embedded system. BLE and Thread are not solidifying into higher level of connectivity solutions for smart homes, wearables and industrial applications.• Bluetooth LE Audio, solving issues with wireless audio for at least three major classes of devices• Matter protocol that seeks to build a common smart home device platform across the multiple ecosystems• IFENSA: Intelligent Fingerprinting for Enhancing NATO Secure Access the use of Ultra-Wideband(UWB) in indoor localization for secure access control.nge communication with minimal power consumption, LPWAN technologies like LoRaWAN and NB-IoT are gaining traction. These technologies are particularly well-suited for applications such as environmental monitoring, smart agriculture, and asset tracking.

AI-Optimized Processors

Current and emerging big semiconductor companies, and startups alike, are by designing new chip architectures to offload as much of the AI and ML workloads as is possible. These AI-optimized processors are designed for achieving high performance when worked on computations of neural networks and at the same time to guarantee the energy consumption.• Reduced precision matrix multiplication units incorporated into neural network design • Chip-level memory organizations intended for low data transportation• Adaptive precision control to dynamically fine tune performance efficiency and energy usage in various deep learning tasks minimal power consumption, LPWAN technologies like LoRaWAN and NB-IoT are gaining traction. These technologies are particularly well-suited for applications such as environmental monitoring, smart agriculture, and asset tracking.

New Chip Architectures and Hardware Acceleration

The increasing demands placed on embedded systems, particularly in AI and ML applications, are driving innovations in chip design and hardware acceleration technologies.

AI-Optimized Processors

Major semiconductor companies and startups alike are developing new chip architectures specifically designed to accelerate AI and ML workloads. These AI-optimized processors aim to provide high performance for neural network computations while maintaining energy efficiency.

Heterogeneous computing system is gradually becoming the mainstream development of processors and accelerators embedded systems. This means that one can get the best out of his system and at the same time use the least amount of energy possible to accomplish the task. • System-on-chips for handling the main tasks related to the central management of the whole system, and decision making. • CPUs or dedicated AI processors for parallel compute operations • Reconfigurable system on programmable chip for application specific acceleration using FPGAs • DSPs for fast signal processing in different applications of audio and video.e long-range communication with minimal power consumption, LPWAN technologies like LoRaWAN and NB-IoT are gaining traction. These technologies are particularly well-suited for applications such as environmental monitoring, smart agriculture, and asset tracking.

Edge TPUs and NPUs

Google's Edge TPU (Tensor Processing Unit) and other NPUs from other manufacturers are now emerging to provide exclusive AI acceleration in embedded systems. These ASIPs empower ML models to run effectively at the edge—on smart devices, sensors, and other resource-scarce hardware for use cases including computer vision, NLP, and predictive maintenance. • High-performance for real-time use cases for AI • Eating less power compared to the general purpose processorsIt comes with support for on-device learning and adaptation • The use of M1 chip has support for on-device learning and adaptation.ded systems that require long-range communication with minimal power consumption, LPWAN technologies like LoRaWAN and NB-IoT are gaining traction. These technologies are particularly well-suited for applications such as environmental monitoring, smart agriculture, and asset tracking.

Open Source RTOS and Middleware

Real-Time Operating Systems (RTOS) and middleware solutions play a crucial role in embedded systems development. Open source options, such as FreeRTOS, Zephyr, and Apache Mynewt, are gaining popularity due to their flexibility, community support, and cost-effectiveness.

In the realm of short-range communication, new protocols are emerging to address the specific needs of embedded systems. Technologies like Bluetooth Low Energy (BLE) and Thread are evolving to provide more robust and efficient connectivity options for smart home devices, wearables, and industrial sensors.

Conclusion

Today and in the near future, product development with embedded systems is changing quickly because of the intersection of cyber-physical systems, Internet of Things and new computing. As we cast the vision to the future, it can be seen that embedded systems will occupy a much more significant position in guiding the conceptualization and development of advanced technological solutions. The patterns described within this article of AI and ML, new security approaches, and other aspects represent one more note on the evolvement of the discussed field. Those in the embedded systems development and organizations need to keep up with such advancements to be in a position to provide innovative, efficient and secure systems to cater for the demands of an interconnect world. The mainstreaming of embedded systems and continuous integration will require true teamwork, combined with greater harmonization and open innovation to meet the challenges, as well as to open up fresh opportunities. By accepting these new tendencies and novelties, the embedded system community can advance the development of new intelligent, safe, and optimal CPS that will be the foundation of the further development of industry, healthcare, transport, and many other spheres.

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