Review On Evolution of Embedded System: Integrating Technical Roadmap and Wider Perspectives

Dr. Pushparani MK[1], Monalisa Prabhugouda Kamatar[2], Rashmi E S[3], Deeksha K S[4], Hema M Iragar[5]

[1]Associate Professor- Computer Science and Design, Alva's Institute of Engineering and Technology, Mijar Moodbidri, Karnataka, India.

[2,3,4,5]Student - Computer Science and Design, Alva's Institute of Engineering and Technology, Moodbidri, Karnataka, India.

Emails: @aiet.org.indrpushparani[1], monakamatar@gmail.com[2], esrashmi2@gmail.com[3], ksdeeksha4@gmail.com[4], hemairagar233@gmail.com[5]

Abstract

This paper examines the evolution of embedded systems and their increasing complexity, focusing on the impact of integration challenges on Real-Time Operating Systems (RTOS) design. As embedded applications expand across automotive, aerospace, and consumer electronics domains, the demand for seamless integration of multifaceted requirements intensifies. Concurrently, emerging paradigms such as the Internet of Intelligent Things (IIoT) advance in embedded machine learning (TinyML) and edge computing to enable intelligent, resource-constrained devices. This paper explores how these technological trends are reshaping RTOS design, emphasizing resource management, interface definition, and system reliability. Furthermore, it reviews current developments and future directions in embedded systems, highlighting the role of integrated and intelligent manufacturing systems within Industry 4.0 frameworks. By synthesizing insights across these domains, the paper outlines critical research challenges and potential solutions to support next-generation embedded applications.

Keywords: Embedded Systems, RTOS, IIoT, TinyML, Edge Computing, Industry 4.0, System Integration.

1. Introduction

Embedded systems have become the invisible backbone of modern technology, powering devices ranging from household appliances to complex industrial and medical equipment. Over the years, their evolution has been shaped by rapid advancements in hardware miniaturization, software development, real-time processing, and connectivity. Initially designed for specific, single-purpose tasks, embedded systems have now expanded into intelligent, interconnected platforms that support automation, IoT, artificial intelligence, and sustainable solutions. Understanding their evolution requires not only technical roadmap-highlighting innovations in microcontrollers, sensors, and communication protocols-but also wider perspectives, such as societal needs, economic impact, energy efficiency, and ethical considerations. By integrating both technological progress and global perspectives, we gain a holistic view of how embedded systems have transformed from basic control units into critical enablers of the digital age.

- **From Simple to Advanced** – In the beginning, embedded systems were used only for single, specific tasks (like controlling washing machines or calculators). Today, they have become smart and multifunctional, supporting technologies like IoT (Internet of Things), automation, and AI [1].
- **Technical Roadmap** - Their progress is linked to advancements in microcontrollers, processors, sensors, memory, and communication technologies. Each generation became faster, smaller, cheaper, and more efficient.
- **Wider Perspectives** - Apart from technology, their evolution is shaped by global needs such

as low power consumption, reduced cost, sustainability, and user convenience. This makes them not only technically advanced but also socially and economically impactful.

- **Present Role –** Today, embedded systems are everywhere: in mobile phones, vehicles, medical devices, smart homes, industries, and defense systems. They are the backbone of modern digital life.

1.1. Technical Roadmap of Embedded Systems

- Early Generation (Simple Controllers)
- Microcontrollers and VLSI Era
- Networking and Real-Time Systems
- IoT and AI-Enabled Embedded Systems

1.2. Wider Perspectives of Embedded Systems

- Economic Perspective
- Societal Perspective
- Energy and Sustainability Perspective
- Ethical and Security Perspective

1.3. Applications and Future Trends

- Current Applications in Various Fields
- Emerging Trends and Future Scope

2. Methodology

Literature Survey Collection of relevant research articles, books, and technical reports from databases such as IEEE X plore, Science Direct, and Springer. Thematic Classification Organizing information into two main themes:

- **Technical Roadmap:** covering advancements in hardware, software, IoT, and AI.
- **Wider Perspectives:** including economic, societal, environmental, and ethical aspects.

Chronological Analysis Studying the development of embedded systems across different generations, from early controllers to present-day intelligent systems. Integration and Evaluation Linking technological progress with societal needs to provide a holistic understanding of the evolution and impact of embedded systems. The evolution of embedded systems can be understood as a wave-like progression over time. In the 1970s, simple controllers were introduced, marking the foundation of embedded computing. The 1980s brought microcontrollers and VLSI technology, enabling compact and efficient

designs. During the 1990s, networking and real-time systems expanded their applications in telecommunications and automation Shown in Figure 1.
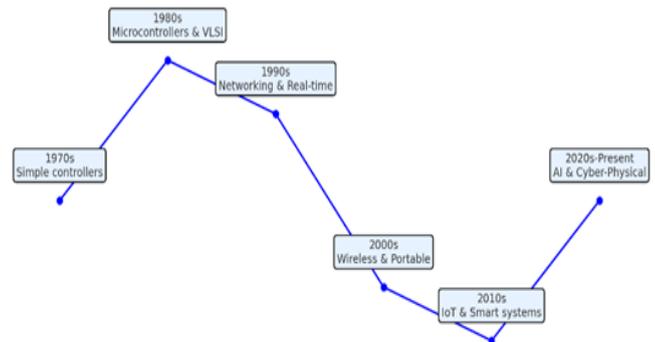

Figure 1 Flow Diagram

The 2000s saw a shift toward wireless and portable devices, such as mobile phones and medical gadgets. In the 2010s, the Internet of Things (IoT) revolutionized embedded systems, connecting devices into smart ecosystems. Today, in the 2020s and beyond, embedded systems are driven by artificial intelligence and cyber-physical integration, powering advanced technologies like autonomous vehicles and smart industries [2].

3. Discussion

Therefore, it is structured into four aspects. The aspect name helps in a first step to identify a suitable pattern. The aspect problem is described by the partial model's characteristics and functions. Characteristics describe the properties of the pattern. A functional hierarchy lists and describes the functions, which can be implemented by the Solution Pattern. Here, the main function is divided into subfunctions until a valid solution can be found for the sub-function. Within the aspect context applications, in which the Solution Pattern was implemented successfully, are getting specified. The aspect solution is defined by the active structure and the behavior. The active structure is the core of the solution description. It specifies which system elements are necessary to implement the functions of the pattern and how those system elements are interrelated. With the description of the behavior the solution is completed. For this purpose, the behavior of the system elements or of logical groups of several

system elements is described. We use the specification technique CONSENS within the Solution Pattern. By using CONSENS, the system is modeled in a holistic and domain-spanning way. The specification of the principal solution forms the basis for the communication and cooperation of the developers from different disciplines during the complete development process. Since solution patterns have degrees of specialization it is possible to ensure continuity throughout the development process Shown in Figure 2 Daniel Kliewe et al./ Procedia Technology 26 (2016) 341 - 348.

Daniel Kliewe et al. / Procedia Technology 26 (2016) 341 – 348
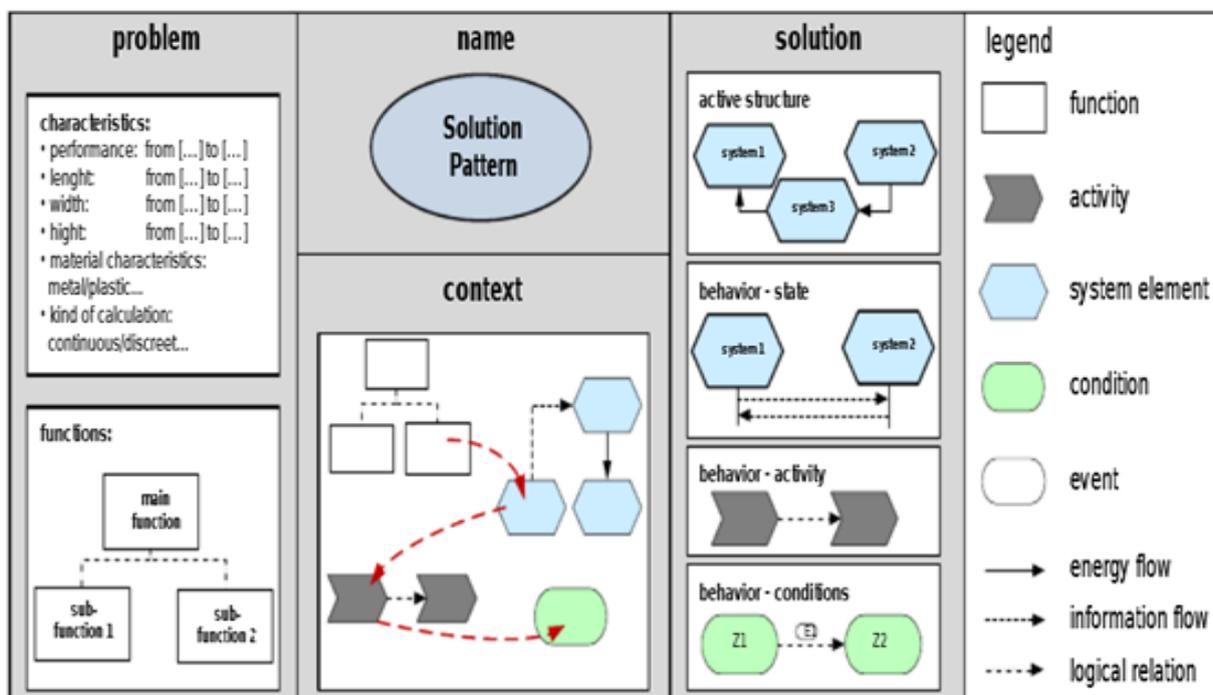
Figure 2 Daniel Kliewe et al./ Procedia Technology 26 (2016) 341 - 348

3.1. Model-based representation of protection measures as Solution Patterns

The focus of the developed approach is the seamless integration of protection measures in modern methods for an interdisciplinary systems design. To meet this challenge a lot of small steps must be taken. The first step is the transfer of the current text-based content of protection measures in a model-based representation. The second step deals with the adaptation of the structure of a solution pattern. The structure must be adapted, so that all information needed for protection can be represented. The third step combines the first two steps and applies the model-based representations for the reuse of well-established solution knowledge and defines Protection Patterns [3].

4. Wider Perspectives

4.1. Technological Perspective

- **Hardware:** Microcontrollers, microprocessors, sensors, actuators, memory, I/O devices.
- **Software:** Real-time operating systems (RTOS), firmware, device drivers, middleware, application programs.
- **Integration:** Hardware–software co-design for efficiency, speed, and low power consumption.

4.2. Application Perspective

- **Consumer Electronics:** Smartphones, smart TVs, washing machines.
- **Automotive:** ABS, airbag control, infotainment, electric vehicles.
- **Healthcare:** Pacemakers, patient monitoring, wearable fitness devices.
- **Industrial:** Robotics, automation, process control.
- **Aerospace/Defense:** Avionics, missile guidance, drones.
- **IoT & Smart Systems:** Smart homes, agriculture, energy management.

4.3. Design Perspective

- **Constraints:** Low power, low cost, small size, high performance.
- **Reliability & Safety:** Mission-critical applications (e.g., medical, aerospace).
- **Real-Time Operation:** Hard real-time vs. soft real-time requirements.
- **Scalability:** From simple 8-bit controllers to multicore SoCs.

4.4. Industrial & Economic Perspective

- **Market Growth:** Embedded systems are the backbone of IoT and Industry 4.0.
- **Job Opportunities:** Hardware design engineers, firmware developers, embedded software engineers.
- **Global Dependence:** Every sector (transport, energy, security, health) relies on embedded systems.

4.5. Future Perspective

- **AI + Embedded:** Edge AI and Machine Learning on devices.
- **5G/6G Integration:** Ultra-low latency applications.
- **Green Computing:** Energy-efficient and sustainable systems.
- **Cybersecurity:** Securing IoT and embedded devices from attacks [4].

5. Road mapping in Embedded Systems

Road mapping is a strategic planning process that outlines the development path, milestones, and technology choices for embedded system projects. It helps teams align hardware, software, integration, and timelines to meet product goals [5].

6. Important Embedded Systems

- **Complexity:** Embedded systems often combine hardware and software, requiring coordinated development.
- **Long Development Cycles:** Roadmaps help manage timelines and dependencies.
- **Technology Evolution:** Embedded components (processors, sensors, protocols) evolve rapidly.
- **Resource Management:** Helps allocate engineering effort, tools, and budgets effectively.
- **Risk Reduction:** Identifies potential bottlenecks and integration challenges early.

6.1. Typical Roadmap Elements for Embedded Systems

6.1.1. Requirements & Goals

- Define product features.
- Performance, power, size, cost targets.

6.1.2. Architecture Selection

- Processor/MCU choice (ARM Cortex, RISC-V, etc.)
- Memory, peripherals, interfaces.

6.1.3. Software Stack

- OS (RTOS, Linux, bare metal).
- Middleware, drivers, communication protocols.

6.1.4. Hardware Development

- PCB design.
- Prototyping and testing.

6.1.5. Integration & Testing

- Hardware-software integration.
- Functional, performance, and compliance testing.

6.1.6. Iteration & Optimization

- Power consumption tuning.
- Debugging and feature enhancement.

6.1.7. Production & Deployment

- Manufacturing readiness.
- Firmware updates and maintenance plan.5. Integration & Testing Hardware-software integration [6].
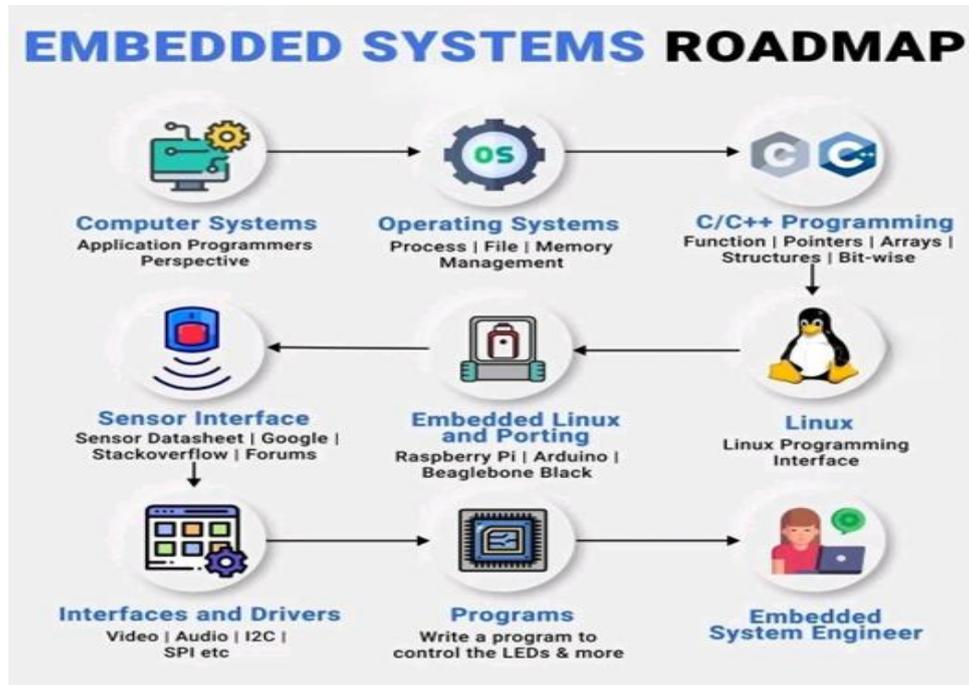- Functional, performance, and compliance testing Shown in Figure 3.

Figure 3 Embedded Systems Roadmap

Conclusion

The evolution of embedded systems reflects a journey from simple, application-specific controllers to highly intelligent, connected, and adaptive platforms that drive modern innovation. The technical roadmap shows a clear transition—from microcontrollers and ASIC-based designs to powerful SoCs, AI-enabled processors, and IoT-integrated architectures. Alongside, the wider perspective emphasizes the impact on industries, society, and sustainability, as embedded systems enable automation, energy efficiency, real-time decision making, and smarter living. By integrating both technical advances and broader implications, it is evident that embedded systems are not only shaping the digital ecosystem but also setting the foundation for future technologies like autonomous systems, Industry 4.0, and smart cities. The continuous evolution will therefore demand innovation, interdisciplinary collaboration, and responsible design to ensure these systems remain secure, efficient, and beneficial for humanity.

Reference

[1]. FlexRay Consortium. http://www.flexray.com/.

[2]. A. Grigg and N. C. Audsley. Towards the timing analysis of integrated modular

avionics systems. In Proceedings ERA AvionicsConference and Exhibition, pages 3.1.1.2, 1997.

[3]. ISO 11898. Road Vehicles - Interchange of Digital Information - Controller Area Network (CAN) for High-

[4]. Speed Communication. International Standards Organization (ISO), ISO Standard-11898, Nov 1993.

[5]. LIN Consortium. LIN - Local Interconnect Network. http://-www.lin-subbus.org/. MOST Cooperation. MOST - Media Oriented Systems Transport. http:// www. mostcooperation.com/.

[6]. OSEK/VDX. Open Systems and the Corresponding Interfaces for Automotive Electronics. http://www.osek-vdx.org/.