Embedded Systems: Core IC Modules and Practical Applications

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Abstract. With the continuous advancement of technology and the growing demands of the market, embedded devices are playing a central role in cutting-edge fields such as industrial manufacturing, the Internet of Things (IoT), intelligent driving, and healthcare. The market size of embedded systems is steadily expanding. This paper conducts a systematic analysis of the core integrated circuit technologies of embedded devices, with a particular focus on recent developments in main control chips, memory chips, and signal processing chips in terms of functional evolution, manufacturing principles, and technological innovation. Furthermore, by examining typical application scenarios in biomedical engineering, intelligent manufacturing, and aerospace, the paper reveals the technological pathways and development trends of embedded systems in the digital age, highlighting their driving force in smart terminals and industrial upgrades. Although embedded devices face technical barriers and challenges, supported by 5G and artificial intelligence (AI), their application prospects remain broad, and they are expected to continue playing a pivotal role in the digital era. This study aims to provide a systematic reference for enterprises in product design, technological investment, and market planning.

Keywords: Integrated Circuit (IC), Embedded System, Next-Generation Design.

1 Introduction

With the advancement of the technology industry, increasingly complex and sophisticated mechanical and electronic systems require embedded devices to realize more comprehensive functionalities. The application of embedded systems in cutting-edge fields such as industrial manufacturing, IoT devices, intelligent driving, and medical equipment has intensified the market demand for these devices. Data indicates the global market size will increase from USD 110 billion in 2024, reaching USD 161.86 billion by 2030, with an expected compound annual growth rate of 6.4% between 2025 and 2034 [1]. This growth is driven not only by the urgent demand for high-performance computing and multi-scenario communication interface adaptability, but also by continuous breakthroughs in semiconductor manufacturing processes.

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However, the widespread adoption of embedded devices relies not only on improvements in chip performance but also on collaborative innovation among functional modules to meet diverse application scenarios. Embedded AI chips must balance instant data processing with energy-efficient operation in the medical field. In industrial control, the profound integration of edge computing and sensor networks is central to enhancing efficiency. In the aerospace sector, chips are required to maintain ultra-high reliability under extreme environmental conditions. Therefore, this paper focuses on the core integrated circuit technologies of embedded devices, systematically analyzing the functional evolution and manufacturing principles of main control chips, memory chips, and signal processing chips, while exploring their typical applications across various domains. By cross-validating technical logic with market demands, this study reveals the technological pathways and development trends of embedded systems in the digital era, providing valuable references for research and practical applications in related fields.

2 Core Chips in Embedded Systems: Functions and Manufacturing

2.1 Main control chips

Main control chips serve as the "central brain" of embedded devices, with their functionality and performance determining the overall processing capability and responsiveness of the system.

Microcontroller Units (MCUs) are the most prevalent type of main control chips, renowned for their high integration, low power consumption, and compact size. These characteristics make them ideal for scenarios requiring precise control and energy efficiency. In recent years, advanced manufacturing processes like Fully Depleted Silicon-On-Insulator (FD-SOI) have been extensively applied in MCUs. An ultra-thin Buried Oxide (BOX) layer is inserted between the active silicon and the underlying substrate, which effectively minimizes undesired capacitive effects and suppresses current leakage. Consequently, it enhances the chip's stability and energy efficiency, particularly in high-temperature or high-interference environments. Additionally, the incorporation of power management mechanisms such as Deep Sleep Mode and Dynamic Voltage and Frequency Scaling (DVFS) has endowed MCUs with superior endurance, aligning with the development trend of low-carbon and green electronic products [2].

In tasks demanding intensive real-time computation and signal processing, Digital Signal Processors (DSPs) exhibit robust advantages. DSP architectures integrate mechanisms like Multiply-Accumulate (MAC) units, pipelined parallel processing, and loop unrolling, enabling efficient processing of data such as voice, images, and radar signals. Currently, DSPs are widely utilized in high-demand scenarios including industrial control, medical diagnostics, and edge AI analysis. Some high-end DSP chips also support mixed fixed-point and floating-point arithmetic units, achieving a more flexible balance between precision and performance.

In contrast, System-on-Chip (SoC) represents the forefront of embedded main control technology development. SoCs not only integrate MCU/DSP cores but also encompass Graphics Processing Units (GPUs), AI neural network accelerators, communication interfaces (e.g., Wi-Fi, 5G), and storage controllers, realizing system-level functionality within a single chip. High-performance embedded SoCs have begun adopting 7nm or 5nm FinFET processes, combined with heterogeneous integration technologies like Chiplet packaging and Through-Silicon Vias (TSVs), achieving higher energy efficiency and on-chip system integration within power constraints [3]. For instance, the NVIDIA Jetson Orin series integrates up to a 2048-core GPU and a 12-core Cortex-A78AE CPU, supporting 200 TOPS of AI inference capability, meeting the dual demands for real-time performance and intelligence in AIoT convergence scenarios.

2.2 Memory chips

The era of high information density has imposed greater demands on data storage in embedded devices, driving memory chips toward advancements in high performance, high density, and low power consumption. In embedded systems, memory is generally categorized into two types: volatile memory and non-volatile memory. Driven by advanced manufacturing processes, DRAM is progressing toward the 1αnm process node, adopting Extreme Ultraviolet (EUV) lithography to significantly increase storage density. At the same time, the use of high-k dielectric materials and metal gate technologies reduces power consumption, thereby meeting the demands of high-frequency data read/write operations in AI edge computing applications [4].

In the realm of non-volatile memory, traditional Flash is gradually being replaced by 3D NAND technology, which vertically stacks hundreds of memory cells to substantially increase storage capacity per square millimeter. A representative example is Samsung’ s V-NAND, which features over 200 stacked layers and combines Through-Silicon Via (TSV) technology with a Charge Trap Flash structure, providing embedded systems with high-reliability local data caching.

More cutting-edge MRAM (Magnetoresistive Random Access Memory) has gradually entered commercial deployment in high-end embedded scenarios. In 2024, TSMC launched embedded MRAM (eMRAM) based on the 22nm logic process node, which can be integrated into low-power MCUs and edge AI chips. With a write endurance of over a million cycles and wake-up latency at the millisecond level, eMRAM achieves a remarkable balance between non-volatility and energy efficiency, outperforming traditional flash memory [5]. Looking ahead, SOT-MRAM (Spin-Orbit Torque MRAM) will enable sub-nanosecond write times through a read/write separation path, further reducing power consumption. This architecture is expected to be applied in high-performance edge computing and Internet of Things (IoT) devices.

2.3 Signal processing chips

In embedded systems, signal processing chips have continuously evolved in terms of precision, power consumption control, and high-level integration, making them indispensable core components in today’s smart devices.

ADC/DAC and ultra-high-speed conversion technologies. Modern analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) are no longer limited to traditional Sigma-Delta architectures. By integrating hybrid Pipeline-SAR architectures and time-interleaved sampling techniques, along with the JESD204C high-speed serial interface protocol (supporting single-lane data rates up to 32 Gbps), both conversion speed and accuracy are significantly enhanced [6].

Integrated ultra-wideband amplifiers. Amplifiers and filters, as key modules in the signal processing chain, have technological advancements that directly impact overall system performance. In recent years, ultra-wideband (UWB) amplifiers based on third-generation semiconductor materials have achieved continuous bandwidths from DC to 67 GHz, with noise figures as low as 0.8 dB [7]. Amplifiers incorporating optoelectronic (OE) technologies can operate at frequencies exceeding 10 GHz, enabling low-noise, high-bandwidth signal processing, and are widely used in optical communications, radar systems, and 5G base stations.

Edge computing and integrated real-time signal processing technologies. With the advancement of edge computing and AI inference, an increasing number of embedded devices are taking on real-time data processing tasks. Based on heterogeneous computing architectures, such as adaptive computing acceleration platforms like the AMD Xilinx Versal ACAP, these systems integrate programmable logic (FPGAs), AI engines (Tensor Cores), and multi-core Arm processors to enable nanosecond-level real-time signal processing [8]. Next-generation sensing processors, such as the Sony IMX500, integrate CNN accelerators directly within the image sensor, enabling real-time edge-side 4K video semantic analysis (latency <5 ms), with applications in medical endoscopy and autonomous driving [9].

The convergence of these cutting-edge technologies not only promotes the application of signal processing chips in ultra-high-precision sensors but also drives modern embedded systems toward greater complexity and efficiency.

3 Application Scenarios of Embedded Systems

3.1 Biomedical engineering

Against the backdrop of rapid advancements in smart healthcare, embedded systems, as a core technology, are being deeply integrated into various cutting-edge medical devices, driving transformative changes in health monitoring and disease management. Currently, embedded AI chips play a crucial role in wearable medical devices [10]. Advanced embedded systems are capable of instantly interpreting vital signs, including metrics like heart rate, arterial pressure, and oxygen saturation. Leveraging edge computing technologies, these systems support health data modeling to enable personalized trend prediction and anomaly alerts. Such systems not only reduce reliance on cloud computing resources but also significantly enhance real-time processing capabilities and data privacy.

At the device level, the artificial pancreas stands out as one of the breakthrough innovations in recent years. The integration of continuous glucose monitors and insulin pumps within an embedded looped control framework allows for automatic insulin delivery [11]. Powered by embedded algorithms that adjust insulin release in real time, this system effectively reduces blood glucose fluctuations in diabetic patients and exemplifies the application of embedded technologies in chronic disease management.

Moreover, cancer early-screening devices based on deep learning have demonstrated great potential in clinical trials. These systems incorporate AI inference chips that can accurately detect subtle abnormal signals in blood or tissue samples, providing technological support for early tumor detection [12]. Unlike traditional screening methods, embedded deep learning systems offer fast, low-power, and portable medical analysis solutions.

3.2 Intelligent manufacturing

Driven by the wave of Industry 4.0, embedded systems have become the core driving force of intelligent manufacturing, widely deployed across key areas such as sensing, control, and communication. Among them, the deep integration of embedded sensor networks and PLC controllers has built an efficient and reliable intelligent production line control architecture. The system utilizes embedded sensors to continuously obtain crucial environmental metrics, including but not limited to heat, force, and vibration. Programmable Logic Controllers (PLCs) then execute precise logic decisions and coordinated equipment control, significantly enhancing automation levels and production stability.

Another typical application is the defect detection system based on embedded edge computing. In traditional quality inspection processes, inspection devices often rely on central servers for image processing, which results in high latency and heavy bandwidth usage. Nowadays, with the help of embedded GPUs and dedicated neural network accelerators (such as the NVIDIA Jetson platform), defect recognition models can run directly on edge devices at the production line, enabling millisecond-level defect detection and response, greatly improving both efficiency and accuracy.

Collaborative robots (Cobots), operating autonomously, are also an essential part of intelligent manufacturing. Unlike traditional industrial robots, Cobots are equipped with embedded multi-sensor fusion systems and adaptive control algorithms, allowing them to safely share workspaces with human workers and dynamically adjust their movement paths according to environmental changes. This flexible automation capability enables Cobots to be widely applied in variable process scenarios such as assembly, grinding, and packaging, greatly enhancing manufacturing flexibility [13].

At a more advanced level, Industrial IoT platforms built on 5G and embedded communication modules are gradually being implemented. These systems utilize high-bandwidth, low-latency 5G networks to connect various embedded terminals, achieving end-to-end digitalization from device status monitoring to remote maintenance [14].

This not only improves production transparency but also provides a scalable technological path for intelligent factory upgrades.

3.3 Aerospace engineering

In the high-tech field of aerospace, embedded systems are widely applied in core areas such as navigation, image analysis, and flight control, due to their high reliability, low power consumption, and real-time responsiveness. Among them, the Inertial Navigation System (INS) is a typical embedded navigation application, extensively deployed in drones, missiles, and spacecraft. This system typically integrates MEMS inertial sensors with embedded processors, enabling it to independently calculate position and attitude in environments without GPS signals, thereby providing precise and stable navigation support for high-dynamic flight missions.

Real-time satellite image analysis systems based on embedded AI platforms represent a new trend in aerospace remote sensing. For instance, the "Jilin-1" satellite has been equipped with low-power GPUs and neural network inference modules capable of running target recognition algorithms (such as YOLOv5) in orbit. These systems can perform tasks such as disaster identification and vehicle detection directly in space, significantly reducing the burden on ground-based processing and improving response timeliness. Such platforms often employ embedded AI chips like the NVIDIA Jetson Xavier NX, combined with FPGA acceleration units, to accomplish tasks such as object detection and cloud identification. This greatly enhances the speed and autonomy of remote sensing, making them particularly suitable for time-sensitive scenarios like disaster monitoring and military reconnaissance.

In more cutting-edge developments, SpaceX’s Starlink satellite constellation employs embedded autonomous decision-making modules, enabling each satellite to possess a certain level of mission coordination and self-scheduling capability. Through distributed embedded system management of link establishment and load balancing, the Starlink system achieves efficient inter-satellite communication and large-scale network self-organization, marking a shift in satellite systems from “remotely controlled” to “autonomous” [15].

4 Conclusion

Through technical analysis and scenario-based validation, this paper systematically illustrates the developmental trajectory of core technologies in embedded devices and their driving role in industrial upgrading. At the integrated circuit level, main control chips have overcome the power wall through breakthroughs such as FD-SOI processes and heterogeneous Chiplet integration. Memory chips have achieved performance leaps in non-volatile storage using 3D NAND and MRAM technologies. Signal processing chips, relying on hybrid architectures and ultra-wideband technologies, meet the demands of high-precision real-time computation. Together, these innovations construct the "performance triangle" of embedded devices—high performance, low power consumption, and high reliability—making them indispensable in scenarios such as closed-loop medical control, industrial edge computing, and autonomous space navigation.

From a market perspective, the application of embedded devices is now driven by a dual-force mechanism of technological supply and demand pull. On one hand, iterative advances in semiconductor manufacturing provide a solid foundation for performance improvements. On the other hand, emerging scenarios such as health monitoring, intelligent manufacturing upgrades, and autonomous satellite decision-making are pushing innovation in chip architecture. Notably, with the deep integration of 5G communication and AI inference technologies, embedded systems are evolving from executing single functions to enabling intelligent perception and decision-making loops, placing higher demands on computing density and energy efficiency.

Although current research is still constrained by the analytical limitations posed by the diversity of technical pathways, this paper, through comprehensive analysis of representative technology chains and application scenarios, reveals the central role of embedded devices in the digital transformation process. As frontier technologies mature, embedded systems are expected to transcend physical constraints and serve as a bridge between the physical and digital worlds, propelling humanity toward a more efficient, sustainable, and creative future.

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