Dynamic driver of digital devices for embedded systems design

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ABSTRACT

A wide-ranging exploration of the diverse applications of embedded systems (ES) is delved in in this study, tracing their evolution from early industrial control to their current pervasive influence on modern technological landscapes. The study underscores their crucial role in various sectors, including consumer electronics, automotive technology, medical and healthcare, education and research, industrial automation, telecommunications, smart cities, edge computing, and the convergence of 5G and artificial intelligence (AI). It accentuates the versatility and transformative potential of ES. The paper reviews the historical, current, and future contributions and evolution of ES in shaping contemporary technological landscapes. Emphasizing the broad impact of ES, the paper highlights their significance for researchers, practitioners, and enthusiasts navigating the dynamic intersection of technology and diverse disciplines.

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1. INTRODUCTION

Embedded systems (ES) are ubiquitous in day-to-day life, appearing in a wide variety of implementations; these may include household electrical devices, nonlinear compensation mechanisms, intricate automation systems, and adaptive control systems. In contrast to general-purpose computer platforms, ES typically possess limited computational power and constrained memory capacity. However, these apparent drawbacks transform into advantages when addressing specific real-time tasks. ES become more cost-effective and easier to design due to their streamlined nature. This simplicity is evident in both hardware and software aspects. The use of fixed designs or limited hardware variations enables the adoption of simplified operating systems (OS). These simplified OS options facilitate predictable, real-time operations, and in some cases, the direct implementation of applications without the need for a formal OS. An ES is a specialized computing device that is dedicated to performing a specific set of functions or tasks within a larger system [1]. These systems are integrated as part of larger products or systems, and they often function instantaneously in a milieu with limitations of size, power consumption, and processing competences.

The study provides a roadmap to dynamic drivers enable the seamless integration of different digital devices into ES without requiring significant modifications to the hardware. They facilitate the system's ability to adjust to various devices and peripherals, hence enabling the creation of more flexible designs. This will facilitate the development process by making it easier to include new devices. By utilizing dynamic drivers, developers may direct their attention towards more advanced functionalities, while being assured that device-specific actions would be taken care of. Dynamic drivers provide for easier implementation of upgrades and problem fixes. Because the drivers are not hardcoded, they may be updated separately from the main system firmware, which simplifies maintenance.

The remaining section in this paper includes main features and background of ES in section 2. The ES categorisation is found in section 3, and it examines the sub-system (mobile) ES, standalone ES, networked ES and real-time ES. The impactful milieu of ES in section 4. The last section of this paper concludes the paper in section 5.

2. MAIN FEATURES AND BACKGROUND OF EMBEDDED SYSTEMS

2.1. Main features of embedded systems

The following are key characteristics of ES in this paper include:

- Dedication to specific tasks: ES are designed to perform predefined batch of functions or tasks. Usually, ES are often customized to satisfy the necessities of a particular application, some of which are controlling an industrial machine, managing the operation of a medical device, or handling the navigation system in a car.
- Real-time operation: countless ES work at instance of time; this implies that, they are designed to respond to inputs or events within a specific frame of time. This response is vital in applications where time consideration is indispensable. Example of such could be found in automotive control systems, robotics, and telecommunications.
- Resource constraints: ES typically have limitations on resources such as processing power, memory, and storage. These constraints are imposed in order to satisfy the precise demands of the target application and for the maximizing of the cost, size, and power consumption of the ES.
- Integration with hardware: ES are tightly integrated with the hardware they control. They often consist of a combination of microcontrollers or microprocessors, memory, input/output interfaces, and other dedicated peripherals to interface with the external environment.
- Customization: ES are often customized for a particular application. The software and hardware components are geared to the particular desires and constraints of the system they are embedded in.
- Autonomous operation: many ES operate autonomously, meaning they function without direct human intervention. For example, a thermostat in a heating system can regulate temperature without constant input from a user [2].

2.2. History background of embedded systems

History and theoretical background of ES could be traced to the evolution of computing and the need for specialized computing devices to controlling specific tasks or functions. In the year 1940s-1950s: The earliest computers were large, room-sized machines designed for general-purpose computation. As technology advanced, engineers and researchers began to explore the integration of computers into control systems for industrial and scientific applications. Early examples include the use of computers to control military systems and industrial processes. So, this led to the development of microcontrollers and microprocessors in the 1970s marking a significant turning point. These integrated circuits combined processing units, memory, and input/output peripherals on a single chip. This integration enabled the creation of compact and cost-effective computing devices [3], [4]:

- Computer architecture: understanding the organization and design of microprocessors and microcontrollers.
- Real-time systems theory: addressing the timing constraints and predictability requirements of ES operating in real-time environments.
- Control systems: applying principles of control theory for systems that require feedback and regulation.
- Signal processing: relevant for ES dealing with signals, such as audio processing, image processing, and communication systems.

3. EMBEDDED SYSTEM CATEGORIZATION

ES may be categorized into two: based on performance requirements, as well as based on the microcontroller's performance [3]. This distinction is illustrated in Figure 1. Another important approach to categorizing ES is based on the functional requirements and their performance; so, the four categories belonging to this are as follows:

a. Sub-system (mobile) ES: mobile ES are compact and straightforward, needing minimal power, memory, and resources. Figure 2 is another classification of ES especially for mobile sub-system. They are commonly found in portable devices like mobile phones, digital cameras, MP3 players, and personal digital assistants Figure 2(a). However, their main drawback lies in their limited resources and memory capacity [3].
b. Standalone ES: these systems operate independently without relying on a host system like a computer. They receive inputs from analog and/or digital input ports, process, compute, convert data, and display outputs through connected devices, as seen in Figure 2(b).
c. Networked ES: this category of ES describes a group of physically separated electronic devices which could perform a collective function. Figure 2(c) describes this succinctly. Connected to resources via a network, these systems utilize networks such as the Internet, WAN, and LAN, either wirelessly or wired connections. This category experiences rapid growth in ES applications. An example is the web server ES, which controls integrated devices via web servers and manages web browsers. Typical applications are in ATM machines, security points in home automation systems linked to the main server, and IoT devices.
d. Real-time ES: these systems deliver precise outputs within specified timeframes. They interact with computer systems through players, sensors, and other input/ output interfaces.

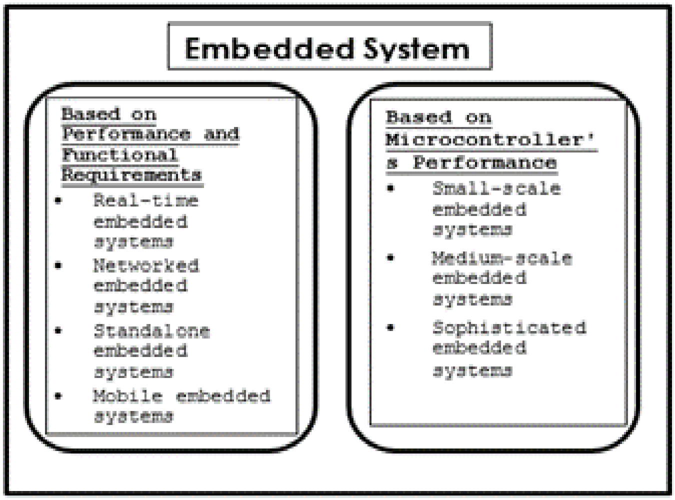
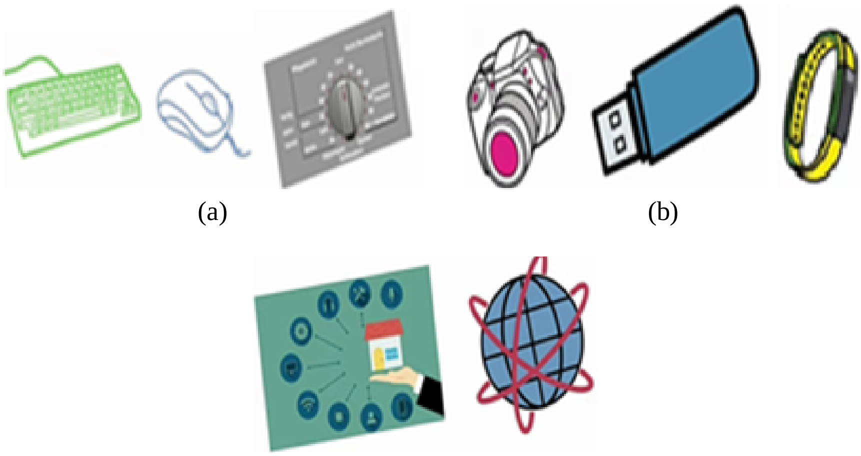


Figure 1. Embedded system classification



(a) (b)

(c)

Figure 2. Another classification of embedded system; (a) sub-system, (b) stand-alone system, and (c) networked system

4. IMPACTFUL MILIEU OF EMBEDDED SYSTEM

4.1. Embedded system in agriculture

Agriculture serves as the primary source of food and is crucial for human sustenance. However, it faces numerous challenges, particularly regarding climate change and conditions in developing nations. Key challenges include monitoring climate conditions, water resources, and soil quality, all of which are critical for agricultural sustainability [5]. UN forecasts that there will be a global population of 9.6 billion by 2050; this may demand a 70% intensification in food production to satisfy rising demand [6]. In response to these challenges, digital agriculture, also referred as smart farming, has surfaced as a scientific field leveraging data and advanced techniques to boost agricultural productivity while minimizing environmental impact [7], [8]. Services and counseling in agriculture rely heavily on data collected from modern farming activities. This data, acquired through sensors embedded in agricultural machinery, soil, or farm animals, provides insights into the working environment and farm activities. Analyzing this data facilitates quicker and more accurate decision-making processes [6].

4.2. Medical and health sector

ES have substantially impacted patient well-being, going beyond clinical outcomes to affect their physical, mental, and social health [9]. They contribute significantly to the progresses in patient care, diagnostics, monitoring, and overall healthcare efficiency, playing a crucial role in meeting diverse needs within the medical sector. These systems' tightly integrated hardware and software components help reduce the size, weight, and energy consumption of medical equipment, thus lowering built-up costs [10]. Real-time processing is another key merit, and when combined with deep learning algorithms, it enables rapid and accurate diagnosis [11], leading to improved outcomes for patients, especially those managing chronic illnesses [9], [12]. ES in medical devices integrate computing elements into equipment for functions like monitoring, control, and data processing [13]. These devices, termed medical electronic devices (MEDs), monitor, track, and transmit patient health data for analysis and treatment planning by healthcare providers [14], Figure 3 displays the generic block diagram of medical electronics device with categories. Their implementation can optimize healthcare by reducing costs and enabling real-time analysis of patients' conditions [15]. MEDs encompass various devices such as medical imaging tools (e.g., X-ray, CT, MRI, ultrasound), enhancing real-time imaging with better clarity and diagnostics. In patient monitoring (e.g., ECG, pulse oximeters, blood pressure monitors), ES enables continuous vital sign monitoring, critical condition alarms, and real-time data transmission. They also regulate infusion pumps for precise medication delivery and power implantable devices like pacemakers, defibrillators, and insulin pumps, ensuring functionality while monitoring and transmitting patient data [12].

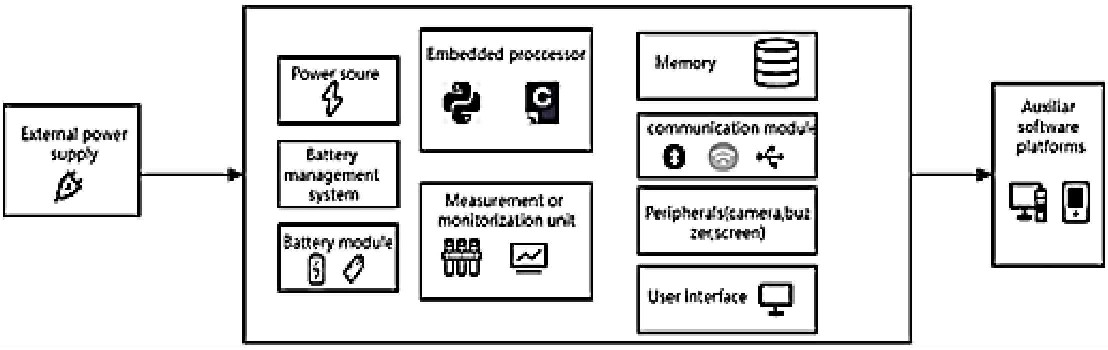


Figure 3. Module diagram of medical electronic devices [13]

4.3. Education and research

Higher education for the next generation is inseparably tied to advancements in new technologies. This requires ES and computing skills, particularly the development of artificial intelligence (AI). The new technologies present opportunities and challenges for teaching and learning in higher education, possibly revolutionizing the management and internal structure of educational institutions [16]. ES have diverse applications in education and research, spanning across various domains and contributing to enriched learning experiences while facilitating cutting-edge research. Integrating an embedded voice teaching system with the rapidly evolving cloud computing technology can indeed revolutionize voice services [17]. This integration can provide a novel approach to delivering voice services, leveraging the scalability, flexibility, and accessibility offered by cloud computing. It can improve the efficiency and usefulness of speech teaching systems, making them more robust, responsive, and capable of delivering high-quality educational content [17], [18].

4.4. Power and energy

The starring role of ES are crucial in the power and energy sector, facilitating efficient management, control, and optimization of energy resources. Li [18] investigated the embedded energy and power management system (EEPMS), focusing on power consumption management and automatic meter reading in residential areas. The EEPMS comprises a single-phase digital kWh power meter integrated with an implanted Zigbee modem. This setup employs a wireless sensor network (WSN) to transmit power utility readings wirelessly back to the energy provider. On the energy provider's end, they have control over prioritizing devices during low power distribution scenarios. The researchers discussed the concept of dynamically assigning priorities to interrupts, aiming to reduce time delays for lower priority tasks that may become higher priority tasks under certain conditions. They also noted variations in interrupt timings that could be leveraged to enhance system performance [19]. The research highlighted the significance of power management in ES development and presented feasible methods and algorithms to minimize power consumption in practical applications [20].

4.5. Networking, connectivity, and telecommunications

ES is indispensable in networking, connectivity, and telecommunications spheres; it facilitates seamless communication and device integration across diverse domains. In networking infrastructure, these systems control the operations of network switches and routers, overseeing data routing and ensuring efficient network traffic using network-on-chip (NOC) technology to implement a routing algorithm which offers a route for a data packet to its terminus; thus proposing a degree of adaptation that avoids network congestion and offers not corrupted packet on network overcrowding status to the nearby routers [21]. They provide needed computational power and practicality to direct networking protocols, data processing, and network management [22]. Also, they implement critical security features like firewalls, interference detection systems (IDS), and intrusion prevention systems (IPS) by checking the network processor's effecting bit for exposure of unfamiliar events based on the instruction execution flow [23], and implementing an integrity inspection mechanism utilizing SHA-256 [24] hash to confirm code integrity ahead of implementation, this invariably eradicate the option of instruction memory alterations and bit handsprings. In addition, ES enable Wi-Fi connectivity in devices like routers, smartphones, and IoT devices, supporting short-range and limitless wireless communication for various applications such as smart home devices and wearables [25], [26]. Also, for secure broadcast over public networks, ES manages virtual private network (VPN) gateways [27], facilitating encrypted data transmission. ES are integral to the functionality, security, and efficiency of networking and telecommunications infrastructure.

4.6. Smart home and city

ES is of primate importance in smart homes and cities' advancement, contributing to improved efficiency, security, and sustainability. In smart homes, these systems manage and coordinate devices like lighting, HVAC systems, and household appliances, fostering seamless interactions among IoT devices to create a unified home automation ecosystem. They also process video data from surveillance cameras, enable advanced features such as motion detection, facial recognition, and real-time monitoring; these enhance security measures [12]. ES develops a complete system for smart homes by integrating features like software advertisement insertion, broadcast prompts, user account management, control and video interfaces, history recording, and so on. They incorporated the basic functions into a unified system, utilizing the share preferences class method for data storage, including user information, device usage statistics, and date-related data. The system also includes algorithms for user prompts, data visualization (such as drawing date curves), and various human-computer interactive ad-ons. Moreover, an access control system design was implemented, significantly improving the security aspect of smart homes.

4.7. Banking and finance

ES play a pivotal role in the finance sector, bringing about automation, heightened security, and enhanced efficiency across various processes. The finance industry features numerous applications that underscore the significance of ES. These systems serve as the backbone of ATMs, ensuring users have secure access to their bank accounts, and facilitating activities like cash withdrawals, fund transfers, and account inquiries. Moreover, ES find practical use in point-of-sale (POS) terminals, contributing to secure and efficient electronic payment processing. These systems play a crucial role in facilitating credit and debit card transactions, guaranteeing prompt and reliable payment processing for retail businesses. In the realm of electronic funds transfer (EFT) systems, ES are integral, providing secure electronic fund transfers between different accounts, spanning online banking, mobile banking, and other digital financial services. Additionally, ES play a key role in security applications, encompassing biometric verification systems like fingerprint scanners and face pack recognition. This contribution enhances the security of financial transactions, access control, and surveillance systems within banking institutions [28], [29].

4.8. Industry and manufacturing

The incorporation of ES in industrial automation and manufacturing plays a pivotal role in advancing smart factories and the industry 4.0 paradigm, resulting in heightened productivity, minimized downtime, and improved overall operational efficiency. ES integrated into programmable logic controllers (PLCs) effectively manage and control industrial processes [30], [31]. They automate tasks such as machinery operation, temperature regulation, and production line control while ensuring real-time monitoring of sensors and actuators for immediate feedback and adjustment. ES also power human-machine interfaces (HMIs) that offer operators intuitive interfaces for monitoring and controlling manufacturing processes [32]. These interfaces facilitate real-time alerts and alarms in the event of abnormal conditions or faults. In supervisory control and data acquisition (SCADA) systems, ES enable centralized monitoring and control of multiple industrial processes and components. They support data logging and historical analysis, contributing to process optimization. Fieldbus protocols like PROFIBUS and Modbus, supported by ES, facilitate communication between devices on the factory floor [33].

4.9. Consumer electronics

The versatility and integration of ES play a significant role in enhancing the functionality, connectivity, and intelligence of consumer electronics, such as smartphones, wearables, and smart appliances, thereby elevating the overall user experience in various aspects of daily life. In smartphones and mobile devices, ES power the mobile operating systems (iOS, Android), providing the core functionality, while also integrating sensors like accelerometers, gyroscopes, and GPS. This integration enhances the user experience by enabling features such as location-based services and motion sensing. Moreover, ES drive the graphical user interfaces (GUIs) of smart TVs, allowing users to navigate menus, stream content, and access apps. The inclusion of communication protocols like Wi-Fi and Bluetooth enables smart TVs to connect to the internet and other devices in the home network. In wearables and fitness trackers, ES facilitate sensor integration, processing data from accelerometers and heart rate monitors. This processing enables real-time monitoring of activities, offering feedback and insights to users. Presently, ES process sensor data for monitoring health metrics and fitness activities in smartwatches, with Bluetooth and Wi-Fi connectivity enabling synchronization with smartphones and other devices. In general, the role of ES is pivotal in advancing consumer electronics, contributing to the smart functionality and interconnectedness that defines the modern user experience [34], [35].

4.10. Automotive industry and 5G and Edge AI

Noteworthy changes are already experienced in the automotive industry via the fusion of ES. This integration has led to a shift towards electronic components playing a crucial role in production systems and meeting the ever-changing demands of the global market [36]-[39]. This dynamic progress of ES within the automotive industry is propelling innovations in vehicle technology, resulting in safer, more efficient, and technologically advanced vehicles. ES, particularly engine control units (ECUs), are pivotal in managing and optimizing engine performance, fuel injection, ignition timing, and emission control. Additionally, these systems are instrumental in ensuring precise control of automatic transmissions, facilitating smooth and efficient gear shifting. ES contribute significantly to advanced driver assistance systems (ADAS) [40]-[42] offering features like acclimatize tour control, advancing collision alarm, as well as programmed emergency stopping system to enhance vehicle safety. They are also utilized for monitoring lane position and implementing corrective actions. In the realm of in-car infotainment systems, ES power intuitive touchscreen interfaces, providing entertainment, navigation, and vehicle settings. Edge computing is an emerging field where ES performs basic role; thus, it provides the computational power and intelligence essential for local information handling at the network edge. This approach focuses on conducting data processing, analysis, and storage in close proximity to the point of data generation, resulting in reduced latency and enhanced overall efficiency [43]. Key applications of ES in edge computing encompass:

- On-device AI: ES with dedicated AI hardware accelerators enable on-device machine learning and inference, facilitating real-time decision-making without relying on cloud services.
- IoT devices: Microcontrollers and ES within IoT devices collect and preprocess data locally before transmitting relevant information to the cloud, thereby improving the efficiency of data transmission [44].
- Edge gateways: ES in edge gateways aggregate data from multiple IoT devices, providing local data processing capabilities and diminishing the need for centralized cloud processing [45].

- Compact servers: deployed at the edge, compact servers with ES handle data processing and storage requirements, contributing to the establishment of small-scale data centers for localized processing [46], [47].
- Mobile edge computing (MEC) servers: ES in MEC servers offer computing functionalities occurring at the edge of the mobile network. ES support applications like augmented reality (AR) as well as virtual reality (VR). These set up also cache frequently accessed content locally, reducing latency for content delivery [47]-[50].

5. CONCLUSION

ES exhibit versatility and play a pivotal role across a broad spectrum of domains, sectors, and disciplines. The extensive application of these systems underscores their significance in augmenting efficiency, automation, and functionality in numerous areas. Their fundamental role contributes to shaping technological progress and enhancing various aspects of our daily lives and industries. ES are crucial for advancing and integrating technology into major facets of human demands, tasks, and operations. As their key features are still to be fully harnessed and explored, these systems are poised to remain a vital and relevant technology in the future. Anticipate continued breakthroughs and the realization of advanced technology possibilities as ES are further integrated in the upcoming years.

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Murimo Bethel Mutanga		✓	✓		✓		✓			✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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