MICROCONTROLLERS SUITABLE FOR ARTIFICIAL INTELLIGENCE

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ABSTRACT

Artificial intelligence (AI) has become increasingly prevalent in various applications, from self-driving cars to facial recognition. However, the implementation of AI on resource-constrained devices such as microcontrollers has been a challenge due to the limited computational power and memory. In recent years, advances in AI technology and the development of specialized hardware have enabled the realization of AI on microcontrollers. This opens new opportunities for AI applications in domains such as embedded systems, the Internet of Things (IoT), and wearable devices. This article provides an overview of microcontrollers suitable for AI, discusses their benefits and challenges, presents a methodology for selecting suitable microcontrollers for AI applications, and highlights the criteria essential for effective implementation. Additionally, initial results from applying this methodology, including a comparative analysis of various microcontrollers, are discussed. Key findings emphasize the potential of specific microcontrollers like ARM Cortex-M7, Arm Ethos-U55, STMicroelectronics STM32F429, and Espressif ESP32-S3/C3 in AI applications. Future directions for the evolution of AI-enabled microcontrollers are also explored.

Keywords: Embedded systems, Internet of Things (IoT), Real-time processing, Power consumption, Hardware acceleration, Machine learning, Neural networks

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1 INTRODUCTION

The growing demand for AI-powered devices has driven the development of microcontrollers with enhanced processing capabilities and AI accelerators. These devices are capable of executing AI algorithms, such as neural networks, on-board, enabling real-time processing and decision-making. This is particularly beneficial for applications where latency is critical, such as robotics and industrial automation (DE VITA, 2022).

IoT devices are used for surveillance, environment monitoring, healthcare, and many more applications. They are used to respond to an external variable but also in more complex settings where there is a need for fast and autonomous reactions. The combination of IoT devices and artificial intelligence brought about a new type of intelligent device capable of

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learning and interacting with its surroundings using past information. This combination is possible due to the improved capabilities of microcontrollers and the effort to reduce deep learning algorithms' memory and energy footprint (Muhoza, 2023)

To use AI algorithms effectively in the real world, it is necessary to have sufficiently powerful computing resources. Microcontrollers are one way to provide this performance. Microcontrollers are small, energy-efficient and affordable computers that are designed for use in embedded systems (Zhang, 2023).

The aim of the article is the overview and search of possible usable microcontroller (MCU) suitable for (AI), MCU has the potential to revolutionize various fields. Discuss the potential benefits, address any challenges, and explore future directions for this evolving technology.

2 BENEFITS OF AI IN MICROCONTROLLERS

In recent years, microcontrollers have also started to be used for AI applications. This is because AI algorithms are becoming more efficient and can be implemented on smaller and less powerful computing platforms.

One of the most prominent applications of artificial neural networks in the consumer space is automatic speech recognition in digital assistants (Bushur, 2023).

The integration of AI into microcontrollers brings several advantages, including:

- Reduced latency and improved responsiveness: AI algorithms can be executed locally on the microcontroller, eliminating the need for data transmission to a central server. This reduces latency and ensures real-time decision-making (Novac, 2021).
- Enhanced data privacy and security: by processing data locally, the need for data transmission is minimized, which protects sensitive data from unauthorized access.
- Increased autonomy and adaptability: AI-powered microcontrollers can adapt to their environment and make decisions autonomously, without the need for constant communication with a central server.
- Reduced power consumption: AI algorithms can be optimized for microcontrollers, leading to lower power consumption.
- Possible running on battery power: run without mains power supply, extended battery life.
- Low cost - microcontrollers are relatively inexpensive, energy efficient, making them affordable for a wide range of applications.
- Small size and weight: microcontrollers are very small and lightweight, making them ideal for use in mobile applications.
- AI close to data: processing data on site, applications are less dependent on internet connectivity.
- Possible mash functionality: Microcontrollers with mash functions can include various connectivity options such as Wi-Fi, Bluetooth and Ethernet. Using for computing, connectivity etc (Qi, 2020).

Disadvantages of microcontrollers for AI applications include:

- Limited computing power: Microcontrollers typically have lower computing power than, for example, personal computers or servers. This can be a problem for applications that require heavy computation.
- Limited memory: microcontrollers typically have less memory than, for example, personal computers or servers. This can be a problem for applications that need to store large amounts of data.
- Energy efficiency focus: microprocessors are designed for a specific purpose, exceeding these limits is problematic.
- Software development complexity: programming microprocessors requires a deep understanding of the architecture and principles of operation. Optimising software for low power consumption can be time consuming and complex.

- Limited AI support or non-existent: existence of available library like TensorFlow Lite for Microcontrollers.
- Limited peripheral support: some microprocessors lack peripherals that are necessary for specific applications. This may require the use of external components that increase power consumption and cost.
- Long inference time: for some AI tasks, the inference time, i.e. the time required to perform a computation, may be too long for microprocessors. This can lead to unacceptable latency and performance loss (Novac, 2021).

3 METHODOLOGY

The methodology for selecting a suitable microcontroller to work with AI should include the following steps:

- Mapping of available MCUs: Use online tools and databases, performance, memory, peripherals, build a comparison table of MCUs.
- Define Application Requirements: The second step is to clearly define the requirements of your AI application. Aspects like: The specific types of AI algorithms the application will use.
- Define evaluation metrics: Performance, benchmarks (CoreMark, DMIPS, EEMBC CoreMark) with respect to specific AI application needs. Factors: CPU architecture, performance, memory, peripherals, AI algorithm support, energy efficiency.
- Evaluate Available Microcontrollers: Once you understand your application requirements, you can start researching and evaluating available microcontrollers.
- Calculating the score: for each MCU, calculate the score according to the criteria combination of metrics.
- Select the Appropriate Microcontroller: select the one that best aligns with your application's requirements. This will ensure your AI application has the necessary processing power, memory, and features to function effectively. Consider other factors not included in the metrics.
- Presentation of results: In the research paper, provide a table of MCU comparisons and justify the selection of the most appropriate candidate.

4 CRITERIA FOR SELECTING A MICROCONTROLLER FOR USE IN AI

When selecting a microcontroller for use in AI, it is important to consider the following criteria:

- CPU architecture: microcontrollers with 32-bit CPU architecture generally have higher performance and efficiency than microcontrollers with 8-bit, 16-bit, 32-bit architecture.
- Performance: the performance of a microcontroller is an important factor in deter-mining what AI algorithms can be run on it. For example, SPEC2017 can be used to measure performance.
- Memory: microcontrollers with sufficient memory can store larger and more complex AI models.
- Peripherals: I/O pins, microcontrollers with appropriate peripherals (connectivity), such as Wi-Fi or Bluetooth, can facilitate communication with other devices.
- AI algorithm support - some microcontrollers offer support for specific AI algorithms, which can make them easier to implement.
- Energy efficiency: Microcontrollers with high energy efficiency are important for battery-powered devices.
- Price: low-cost microcontrollers are preferred.

Other recommendations:
- For a comprehensive assessment of energy performance, consider analysing energy consumption in different operating modes (active, sleep, etc.).
- For specific AI tasks (e.g. image processing, speech recognition), consider using dedicated MCUs with integrated accelerators.
- For testing and prototyping AI applications on selected MCUs, consider using development kits and platforms.
- Socket configuration (available pins): BGA, LQFP, etc.

In addition to general microcontroller parameters, it is also important to consider the specifics of the particular AI algorithms that will be executed on the microcontroller. For example, machine learning algorithms for image classification may require more computational resources than speech recognition algorithms. alternatively, algorithms published in (Stastny, Skorpil, 2007; Stastny et al., 2021).

Special hardware accelerators can improve the performance and efficiency of AI algorithms on microcontrollers. These accelerators often target specific types of AI algorithms, such as neural networks.

5 PARTIAL RESULTS OF METHODOLOGICAL PROCEDURE

The initial stages of the methodological procedure for selecting a suitable microcontroller for AI applications involve mapping the available microcontrollers and defining their key parameters. Here are the partial results based on the attached paper:

a) **Mapping Available Microcontrollers:**
The following microcontrollers were considered: ARM Cortex-M7, Arm Ethos-U55, STMicroelectronics STM32F429, Espressif ESP32-S3, and Espressif ESP32-C3 (Loukatos, 2023; Yoon, 2020)

b) **Defining Key Parameters:**
The key parameters identified for comparison include clock speed, flash memory, SRAM, peripherals, applications, and cost.

Parameter	ARM Cortex-M7	Arm Ethos-U55	STMicroelectronics STM32F429	Espressif ESP32-S3	Espressif ESP32-C3
Processor	32-bit RISC	32-bit RISC	32-bit RISC	32-bit RISC	32-bit RISC
Core	Cortex-M7	Ethos-U55	Cortex-M4	Xtensa LX7	Xtensa LX7
Clock speed	Up to 400 MHz	Up to 500 MHz	Up to 180 MHz	Up to 240 MHz	Up to 160 MHz
Flash memory	Up to 2 MB	Up to 16 MB	Up to 2 MB	Up to 4 MB	Up to 4 MB
SRAM	Up to 512 KB	Up to 4 MB	Up to 256 KB	Up to 512 KB	Up to 384 KB
Peripherals	USB, Ethernet, CAN, SPI, I^2C, UART, etc.	USB, Ethernet, CAN, SPI, I^2C, UART, etc.	USB, Ethernet, CAN, SPI, I^2C, UART, etc.	USB, Ethernet, CAN, SPI, I^2C, UART, etc.	USB, Ethernet, CAN, SPI, I^2C, UART, etc.
Applications	Industrial control, IoT, wearables, etc.	Machine learning, image processing, etc.	Industrial control, IoT, automotive, etc.	IoT, wearables, home appliances, etc.	IoT, wearables, home appliances, etc.
Cost	$10-$20	$5-$10	$5-$10	$5-$10	$2-$5

Tab. 1 MCU characteristics

Their operating frequencies are in the order of hundreds of MHz, working memory is in the order of 0.5 MB and the price is under 20 dollars. The final choice of microcontroller would depend on the specific needs of the application and the available budget.

c) **Define evaluation metrics**:
For each microcontroller, calculate a score based on the combination of the evaluation metrics. This step is generally detailed and involves assigning weights to each metric and then computing a composite score for comparison.
Example Scoring Approach:
- CPU Performance (30%)
- Memory (25%)
- Peripherals/Applications (15%)
- Energy Efficiency (20%)
- Cost (10%)

d) **Initial analysis:**
- Performance: The Arm Ethos-U55 has the highest clock speed (500 MHz) and the most significant amount of SRAM (4000 KB), making it potentially the best option for more demanding AI applications such as machine learning and image processing. The ARM Cortex-M7, with a clock speed of 400 MHz and 512 KB of SRAM, is also a strong candidate for industrial control and IoT applications.
- Memory: Flash memory is critical for storing AI models. The Arm Ethos-U55 stands out with 16 MB, significantly more than the other microcontrollers.
- Cost: The Espressif ESP32-C3 is the most cost-effective option at $3, suitable for budget-conscious projects or applications with less demanding AI requirements.
- Peripherals/Applications: Different microcontrollers are tailored to various applications, with the ARM Cortex-M7 and STMicroelectronics STM32F429 being suitable for industrial control and IoT, while the Espressif models are ideal for IoT and wearable applications.

Generally, embedded systems are limited in two aspects: processing power and memory. For example, the ESP32-WROOM-32E, a popular system on a-chip (SoC) for embedded systems, possesses at most two cores operating at 240 MHz with 520 kB of SRAM and 16 MB of SPI flash (Bushur, 2023).

6 RESULTS

Microcontrollers are increasingly suitable for use in AI. Their small size, low power consumption, and relatively low cost make them ideal for use in mobile applications and other applications where a low power profile is important.

Currently, AI developers are working on developing new algorithms that are optimized for microcontrollers. These algorithms will be able to make better use of the limited resources of microcontrollers.

Initial results show that microcontrollers such as ARM Cortex-M7, Arm Ethos-U55, STMicroelectronics STM32F429, Espressif ESP32-S3 or ESP32-C3 are increasingly suitable for AI applications.

7 DISCUSSION AND CONCLUSIONS

Microcontrollers are expected to play an increasingly significant role in AI in the future. This is because AI algorithms are becoming increasingly efficient and can be implemented on smaller and less powerful computing platforms. The development of microcontrollers with AI is a rapidly developing field with significant potential. The ability to execute AI algorithms on board microcontrollers opens up new possibilities for AI applications in a variety of fields. As technology evolves, we can expect to see even more sophisticated and innovative AI applications powered by microcontrollers. (Muhoza, 2023) This opens up new opportunities for AI applications in domains such as embedded systems, Internet of Things (IoT), and wearable devices. (Campero-Jurado, 2020)

While the potential of AI-powered microcontrollers is vast, there are some challenges to consider. The processing power of microcontrollers is generally lower compared to traditional computers. This may limit the complexity of AI models that can be implemented. Additionally, training and deploying AI models on microcontrollers can be more complex compared to traditional platforms (Zhang, 2020). We have added additional MCUs to be considered for use with AI.

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