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# Embedded System Architectures Optimization for High Performance Edge Computing

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## Abstract

Only a few years ago, embedded computing was a very different landscape. While the traditional computing architectures are reimagined to satisfy the continuously increasing demands for more powerful and efficient computing solutions at the edge, demand for them also increases. With the move to high performance edge computing, we have revisited how we design and implement embedded systems. The heart of this evolution lies in systems that need to process vast unimaginable quantities of data, in real time, sometimes in resource constrained environments. As a result, this has spurred the creation of highly efficient architectures constrained by performance, power efficiency, and small size. To the extent that the artificial intelligence (AI) and machine learning (ML) applications at the edge have further accelerated this trend, the boundaries have seemingly been pushed as far as they can go in terms of what's possible in edge computing. Integrated into smaller, more efficient packages, more powerful processing units have been one of the driving forces for this evolution. The rise of these sophisticated System on Chip (SoC) and System on Module (SoM) solutions has seen the fitting of impressive computing capabilities into very small form factors. The emergence of these advancements has provided new opportunities for embedded systems in a wide range of domains: from autonomous vehicles to industrial automation.

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## Embedded computing evolution

Understanding the underlying architectures and technologies behind high performance edge computing is important as we dig deeper into that world. In the next sections, we look at the most important aspects such as key components, design perspective, along with trends that are about to bloom in the edge computing application's embedded system architecture.

### A Primer on SoC Technology

System on Chip (SoC) technology is a big stride in integrated circuit field. Some SoCs are essentially a way to consolidate various components of a computer or electronic system into a single chip. The actual integration is quite substantial beyond simply housing a processor; in fact, it encapsulates a separate array of functions that used to belong to multiple chips. A typical SoC has several components among which. In the middle of this lay the central processing unit (CPU), which was the brain of the system, at its heart. You will often find a graphics processing unit (GPU) to facilitate computing for visual purposes, a memory controller controlling the data flow and interfaces for input and output. In many modern SoCs, there is other dedicated hardware accelerators for performing the job more efficiently, for example AI Inference or signal processing.[1-4]

The high performance that SoC technology offers, and its ability to do so within a compact form factor, are two of the primary advantages of adopting SoC technology. SoCs are achieved by integrating different components onto a single chip which dramatically reduces the size, and subsequently the power consumption, of the system. That means they're great

for use in space constrained devices like smartphones, tablets and embedded systems. But efficiency gains of SoCs include that in size and power but sprawl is the small price to pay. Thus maintaining a tight integration of components offers optimized data pathways with better latency and better system performance as a whole. Especially in real time applications where fractions of a second are of interest. The result is that SoCs often approach the aggregate limits of manufacturing costs and reliability through being highly consolidated, reducing the number of components that could fail.

With increasingly sophisticated designs on their respective SoC technology moving forward it's as though we're moving the boundaries of what is possible in embedded computing. With these advanced features, such as Neural processing units (NPU) for AI tasks or high speed connectivity standards, latest generations of SoCs come into grace for Elders and Infants. Innovations such as these are opening the doors for more powerful, flexible embedded systems in many application areas.[5-7]

## System-on-Module (SoM) Solutions – The Rise

System on Module (SoM) solutions are now created by building upon the System-on-Chip technology. Contrary to the former, a SoM further extends the concept of integration by including an SoC with components such as memory and power management as well as various connectivity interfaces that are attached to a single, small, printed circuit board (PCB). SOM solution provides better advantage in simplifying the design and development process in a embedded system. SoMs deliver a pre-integrated, pre-validated module minimizing the amount of effort required from engineers to figure out those complex low level hardware design details and can focus on application specific features. This can greatly reduce development time and costs, particularly for companies that don't have a lot of in house hardware expertise.

Flexibility and scalability of SoMs are very high. Typically they have standardized connectors that make them easy to seamlessly integrate into a larger system design. The ability to rapidly prototype is made possible with this modular approach, as well as to upgrade or modify systems in the field. To give just one concrete example, if a more powerful processor becomes available then, oftentimes, the entire SoM can be swapped out without having to adjust the carrier board at all. SoMs also provide another major advantage to improve overall system reliability. Many potential integration issues are eliminated before the module reaches customer, and indeed the design allows the core components to be pre-integrated and thoroughly tested by the module manufacturer. In such critical applications this results in more robust and stable systems.

Industries from industrial automation and medical device to aerospace and defense are using SoMs. As the integration of high performance computer with compact and feature rich space and power requirements finds applications at the edge of the network, and since they are small enough to manage this integration their size, high performance, and ease of integration make them particularly well suited to these edge computing applications. The increasing demand for intelligent, connected devices indicates a future in which SoM solutions are likely to take a bigger place in the future of the embedded system design.[8-11]

## Advantages of 3U VPX Single Board Computers based on SoM.

System on Module (SoM) technology integrated with 3U VPX Single Board Computers (SBCs) are a new era in the field of high performance embedded computing. The combination of these two technologies provides lots of advantages, which makes them especially appropriate for harsh applications in aerospace, military and industrial automation (Table 1).

One advantage of SoM based 3U VPX SBCs is that they are providing high performance in a compact form factor. A SoM can be added to the 3U VPX standard to complement the robust, standardized platform for building embedded systems in a more rugged environment while adding in the integration of cutting edge processing capabilities. It produces a solution that can carry out such complex computational tasks while meeting strict size, weight, and power (SWaP) constraints. Improved system reliability is also achieved by integrating SoMs into 3U VPX SBCs. Using pre integrated and validated modules eliminates many potential points of failure. In particular it is important in mission critical applications with no expense for system downtime. Moreover, these systems are modular for easier maintenance and upgrade, so the life span of the system may be lengthened.

Its high development time reduction and cost advantage is another major advantage.

**Table 1: Architectural Components for High-Performance Edge**

| Component | Functionality |
|---|---|
| Edge Processor | Edge processors perform local computations, enabling faster decision-making and reducing latency by processing data at the edge of the network. |
| Memory Hierarchy | Memory hierarchy optimizes data access speed by organizing different types of memory (e.g., cache, DRAM) to ensure high throughput and low latency. |
| Data Acquisition Interface | Data acquisition interfaces handle the collection of real-time data from IoT sensors, cameras, or other edge devices, ensuring fast data acquisition. |
| Communication Interface | Communication interfaces (e.g., Ethernet, Wi-Fi, 5G) enable the transfer of processed data between edge devices and the cloud or other network components. |
| Power Management | Power management ensures the efficient use of energy, optimizing battery life and power consumption of edge devices while maintaining performance. |
| Security Modules | Security modules protect edge devices from cyber threats by implementing encryption, authentication, and intrusion detection systems to safeguard data integrity. |

Pre integration of the core components on the SoM enables the designers to concentrate on the application specific features instead of the low level hardware integration. It can greatly speed up time to market for new products as well as the companies' deployment capabilities in response to new market demands. Enhanced flexibility in system design is also provided by SoM based 3U VPX SBCs. As VPX backplane standardized interfaces coupled with modular SoMs make easy for the easy integration of new capabilities as required. This accommodates such specialized I/O modules as well as additional processing units and custom hardware accelerators, at the expense of the system architecture compatibility.[12-16]

## High Performance Embedded Systems: Key Components

Themee High performance embedded systems for edge computing applications include several key components working together delivering outstanding performance in a small, power efficient package. Knowing all these important subsystems is essential to designing and operating a system efficiently. Central Processing Unit (CPU) is at the heart of these systems. Based on ARM architecture, ARM intelligence, and its excellent performance to power ratio, modern embedded CPUs tend to be. And these processors are purpose built to perform a variety of tasks: general purpose computing to real time control. Embedded systems that perform some high performance functions will often have multi core CPUs to enable parallel processing, as well as increase overall system responsiveness. Today, graphics processing units (GPUs) are becoming an increasingly important piece of embedded systems that target AI, and machine learning applications. GPUs excel for complex algorithms that require parallel processing, or data huge data heaps all at once. Then some advanced embedded systems equipped with GPUs with specialized AI acceleration such as NVIDIA's CUDA cores or Tensor cores.

Ensuring operation at high performance requires memory subsystems. Typically, the combination of active processing and non-volatile data retention usage includes high speed RAM and non-volatile storage, the two halves of the story. LPDDR (Low Power Double Data Rate) is widely used in advanced embedded systems as its combination of high bandwidth and low power consumption. The other one is once again, connectivity, which is an important part, especially for edge computing applications that require a communication with other systems or to send data to the cloud. It could be all sorts of interfaces, like Ethernet (including high speed variants like 10GbE) and Wi-Fi and Bluetooth and cellular modems. Specialized industrial interfaces such as PROFINET or CAN bus are also provided in many systems for integration with industrial control systems. High performance embedded systems are seeing the emergence of more and more hardware accelerators. These specialized processing units are meant to offload certain types of tasks from the main CPU, allowing for more efficient use of the overall system. They include neural processing units (NPUs) for AI inference, digital signal processors (DSPs) for audio and video processing, and field-programmable gate arrays (FPGAs) for programmable hardware acceleration.[17-22]

## Optimizing Performance: Edge Computing Application

To optimize performance in edge computing applications, a multi faceted approach to system design and implementation is needed. Due to the common operating space of these systems in resource constrained environments, balancing performance, power, and form factor becomes critical. An important way to achieve performance optimization is the use of heterogeneous computing resources in an effective way. It means using the breadths (strengths) of different processing units (CPUs, GPUs, specialized accelerators) for different tasks and getting the processes done as optimally as possible. One such example is to offload computationally expensive operations such as image processing or AI inference to a GPU, a dedicated neural processor or SoC neural accelerator, and in exchange, obtain better performance for the whole system at the expense of bringing down the load from the main CPU. Memory management is key to maximize the performance of edge computing. Caching strategies can be implemented such that it can be done efficiently, and the data flow between different memory tiers can be optimized in order to reduce latency and increase processing speed. In addition, system performance can be improved in data intensive applications when high bandwidth memory interfaces, or optimized memory access patterns are used (Figure 1).

As with any sort of performance critical hardware, the performance of edge computing systems can be maximized on the software level as well. This includes making use of efficient algorithms, code optimization for the target hardware architecture and compilers. For a large number of cases, using hardware specialized libraries and SDKs are not only useful but also lead to tremendous performance improvements through full reaping of underlying hardware capabilities. Another important benefit of performance optimization in edge computing is the power management. Dynamic voltage and frequency scaling (DVFS) techniques can be implemented to strike the performance power balance according to workload demand. Also, smart power gating and selective platform component activation are shown to be effective to reduce overall power consumption with little impact on the performance. Both performance and power optimization are tightly tied to thermal management. Consequently, effective thermal design and management strategies are needed to ensure maximum available operating temperatures, avoid thermal throttling, as well as long term reliability. Improved cooling solutions may involve advanced cooling, such as at the component level and midplane, as well as component placement optimized based on temperature sensitivities, and thermal-aware scheduling algorithms.

## Working with Size, Weight, and Power (SWaP) Constraints

Due to Size, Weight and Power (SWaP) constraints, that are crucial to address in the embedded system realm, especially in the context of edge computing application, these particular edge computing application relevant challenges are addressed. Given

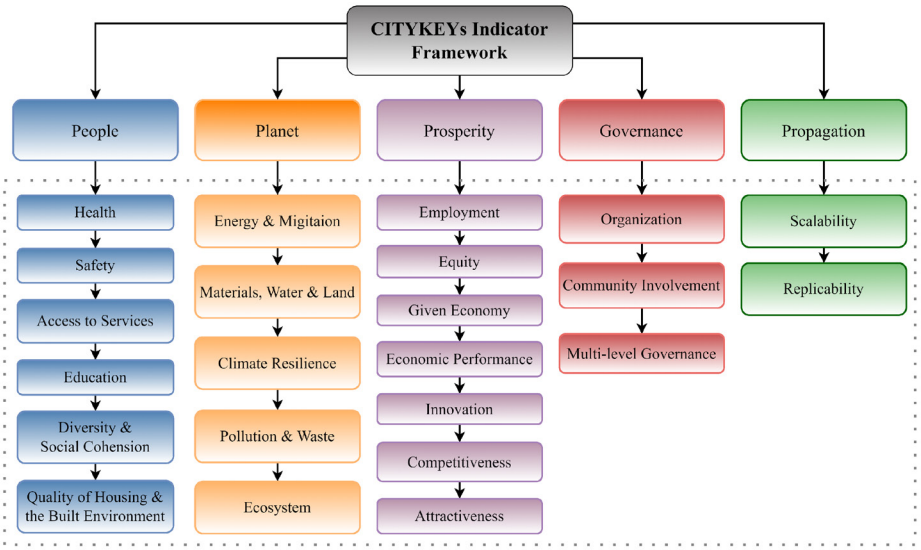


**Fig. 1: Edge Computing Application**

the importance of these constraints in sectors such as aerospace, defense, and portable electronics, they are of special interest. One of the main embedded system design challenges is minimizing size. It also includes optimizing the overall system architecture to minimize footprint, all the while selecting compact components. Reduction of the total size of the system can be done with the aid of advanced packaging technologies, including 3D IC stacking and system in package (SiP). And of course, PCB layout and individual component placement can ensure a maximum use of space and the minimum size of finished product. Size minimization, although weight reduction in its own right, may also involve specific material choices. For example, light weight materials for enclosures and heat sinks can reduce the weight of the system significantly. In some instances, bringing together multiple functions into a single component (think SoCs and SoMs) can expunge the need for specialized modules and decrease weight.

Power optimization is critical both for increasing the lifetime of a battery in portable devices and also for lowering the heat generation and enhancing the reliability of the system as a whole. A system of many layers: selecting energy efficient components is the first. More power reduction can be achieved by implementing sophisticated power management techniques, like dynamic power gating and adaptable voltage scaling. And we can also optimize software to reduce all unnecessary processing and utilize low power modes when our full performance isn't required to attain large energy savings. Power optimization, thermal management, and dealing with SWaP constraints are strongly coupled. Thermal design efficiency not only helps to maintain operation within optimal temperatures, but also can reduce the size of cooling solutions required. It can be using high performing thermal interface materials, employing heat spreading techniques or improving it by using passive cooling methods whenever possible. The requirements of the mission, and therefore the specific application, will determine to some degree the range of the proposed trade-offs needed in order to meet the IM's SWaP constraints and balance these constraints. Consider, though, that it may mean lowering power consumption at the expense of not running at maximum speed in less critical situations, or that it will necessitate the use of more advanced (and potentially more expensive) components than in other products we sell. The trick is to get the right balance — as far as the application needs and within the defined SWaP envelope.

## Reliability and durability improvement for Harsh environments

Edge computing based applications would deploy embedded systems in harsh environments including high humidity and extreme temperatures, high vibration, and electromagnetic interference. Reliability and durability of these systems are critical to providing the reliable and long life performance in such conditions. When designing for harsh environments, one of the primary considerations in component selection. It also includes the use of industrial grade or military spec components that are rated to operate over an extended temperature range and can withstand high amounts of shock and vibration. An example is that switching to solid-state storage devices instead of the traditional hard drives can provide dramatic reliability improvements in high vibration environments.

Although protective enclosures are important in shielding sensitive electronics from hazards in the environment, the poor mechanical performance is often a hindrance. Often these enclosures are designed to incorporate features such as IP67 or MIL-STD-810 ratings to protect against dust, water ingress and other environmental factors. The system can be further advanced to withstand harsher conditions by using advanced sealing techniques and corrosion resistant materials (Table 1).

In extreme environments thermal management becomes all the more critical. It may require installing cutting edge cooling techniques like conduction cooling, or liquid cooling systems. Sometimes the entire system is designed to be passive cooled so that fans, which can be a point of failure in dusty or humid environments, aren't needed. EMC and EMI protection are very important considerations in industrial or military applications. It presupposes non only careful PCB layout design, but also shielding techniques and EMI filters to make the system be suitable to be used in Cluttered electromagnetic noise environments.

The reliability can be enhanced significantly with redundancy and fault-tolerance features. These could include redundant power supplies, use of error correcting memory, or just designing the system with multiple power supplies, with the intention that the system will fail over to a backup if one of the power supplies fails. Sometimes this can be achieved by using watchdog timers and self diagnostic features. Just as

**Table 2: Optimization Techniques For Embedded Systems**

| Technique | Effectiveness |
|---|---|
| Task Scheduling | Task scheduling techniques optimize the execution order of computational tasks to minimize processing time and improve system throughput. |
| Parallel Processing | Parallel processing enables multiple tasks to be executed simultaneously, enhancing the performance and efficiency of edge computing systems. |
| Low-Latency Algorithms | Low-latency algorithms minimize the time delay in data processing, ensuring real-time decision-making in critical applications such as autonomous vehicles. |
| Energy-Efficient Design | Energy-efficient design reduces power consumption by using low-power processors and optimizing the usage of energy resources in embedded systems. |
| Thermal Management | Thermal management techniques prevent overheating of edge devices by optimizing heat dissipation and ensuring stable performance during intensive computation tasks. |
| Resource Allocation | Resource allocation techniques optimize the distribution of computational resources, ensuring high performance while maintaining cost-effectiveness in edge systems. |

much, harsh environments are equally important to software reliability. When designing it to gracefully handle unexpected conditions, a good portion of the work is spent ensuring that the system can absorb unexpected conditions gracefully through robust error handling and utilizing watchdog mechanisms. Secure boot processes and cryptographic verification can also be implemented to protect the system software against tampering.

## Using AI and Machine Learning at the Edge

With Artificial Intelligence (AI) and Machine Learning (ML) advanced capabilities integrated into edge computing systems, embedded system design has taken a major step forward. Simplicity and convergence allow for sophisticated data processing and decision making to take place at the point of data collection directly with reduced latency and bandwidth requirements, and improving privacy and autonomy. A primary obstacle in deploying AI and ML at the edge is finding ways to run these computationally intensive tasks in resource constrained environments. For example, it'll often involve using specialized hardware accelerators in this instance for AI workloads. For example, many modern SoCs and SoMs include neural processing units (NPUs) or tensor processing units (TPUs) that can perform machine learning models much more efficiently, as these units consume much less power than general purpose processors.

Enabling effective AI at the edge requires model optimization. This involves methods like quantization, to limit the precision of model parameters with a reduced memory footprint and computational cost.

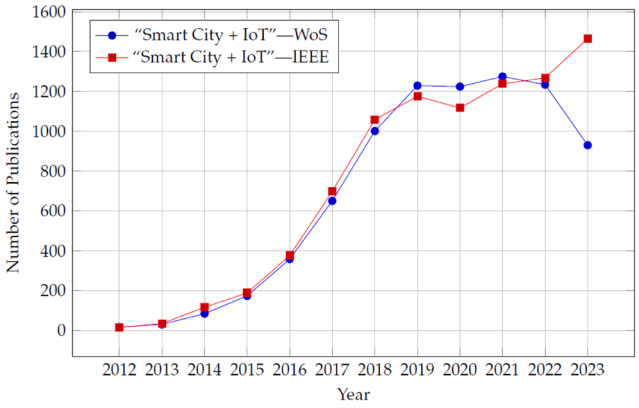


**Fig. 2: AI and Machine Learning at the Edge**

Another optimization technique, as the name indicates, is pruning, which means removing non necessary connections, with sacrificing no accuracy on the model while reducing the model size. Then we can use these optimized models to be deployed on edge devices with limited resources and yet with high performance. Time is then generated to address advantages from transfer learning and federated learning techniques that are used in edge AI systems. Transfer learning allows models from large data sets to be fine tuned for particular edge application with negligible local data. With federated learning multiple edge devices can collaboratively train a shared model without sharing raw data, preserving privacy, and reducing bandwidth requirements.

Many edge AI applications need the functionality of real time inference. To achieve this requires optimized models and efficient hardware but also software frameworks that facilitate realtime execution. Lightweight inference engines in

conjunction with optimized runtime environments, often leverage resource constrained devices to produce real time performance in many embedded AI systems. By integrating AI and ML at the edge, there are numerous such applications in the field of different industries. Edge AI can predict maintenance in industrial settings, or perform real time quality control or autonomous robotic systems. It can empower smart cities and transportation with intelligent traffic management, self driving vehicles, and modern surveillance systems. Edge AI in healthcare can help to enable real time patient monitoring, faster diagnostic support as well as personalized treatment recommendations.

## Achieving Security in High Performance Embedded Systems

For embedded systems that are more powerful and also more connected, security becomes ever more critical. An embedded system used to perform high performance tasks normally processes sensitive data and controls critical infrastructure that makes it an attractive target for cyber attack. To protect the data that is handled by these systems, robust security measures must be implemented. Secure boot is one important part of embedded system security. This makes sure that, when the system first starts up, only existing, unaltered and authenticated firmware will load. You can implement a chain of trust in which each step of the boot process ensures that the next stage was not tampered with. Nowadays, many modern SoC s or SoMs have hardware based security features such as secure enclaves or trusted execution environments to use in secure boot processes.

Ensuring data at rest and data in transit are protected is the job of encryption. The use of strong encryption algorithms in storing and transmitting data makes it virtually impossible for people without specific key to access sensitive information. Modern high performance embedded systems often have hardware accelerated encryption engines so that robust cryptographic protocols are capable of efficient implementation with minimum performance overhead. Preventing system access by unauthorized parties relies heavily on access control and authentication mechanisms. You could be implementing multi factor authentication, role based access control and a secure key management system. Biometric authentication methods can be integrated in some high risk application for enhanced security.

Embedded connected systems are particularly vulnerable to network security attacks. Networks can be protected from attacks with the presence of firewalls, intrusion detection systems, and secure communication protocols (i.e TLS/SSL). Moreover, networks can be divided into segments, and VLANs can be implemented to isolate critical systems and restrict the possibility of the security breach causing widespread damage. Security updates and patch management of imbedded systems are critical for the continuity of security through their entire lifecycle. One way to address newly discovered vulnerabilities and adapt to new security threats is to design systems to be secure, over the air. But the update process itself needs to be secured so it can't be used as an attack vector. However, physical security measures shouldn't be ignored — especially for systems deployed in easily accessible locations. Tamper evident or tamper resistant enclosures, secure storage for cryptographic keys, and mechanisms for detecting and responding to physical tampering attempts may be part of this.

## Future Trends in Embedded System Architectures

There is constant evolution in the field of embedded system architectures which is triggered by evolving technology and changing application requirements. Future high-performance embedded computing is being shaped by several emerging trends across chips, systems and software, capable of even greater capabilities and improved efficiency in the future. A big trend is the widespread use of heterogeneous computing architectures. Such systems form new type of system combining different types of processors like CPUs, GPUs, FPGAs, and specialized AI accelerators into a single chip or module. This approach also enables the best possible task allocation by workloads to specific types of processor in a way that each particular type of processor can do the workloads for which it is best suited. However, these heterogeneous architectures will be increasingly important as applications become more complex, especially in areas such as AI and computer vision, where the node size and transistor packing density make it difficult to achieve the performance that would be needed within very tight power and thermal constraints.

Embedded systems are powering the rise of edge AI, and as their complexity grows, the need for more powerful, efficient AI accelerators targeting their needs grows as well. These processors are specialized

for neural network inference tasks and can provide a dramatic boost in performance over watts than can be obtained from general purpose processors. When AI starts to roll into embedded applications it will certainly be the case we'll see a flood of these AI optimized architectures on edge devices far and wide. As semiconductors advance in semiconductor manufacturing processes, more and more functionality is able to be packed into increasingly smaller, more power efficient packages. This trend towards 3nm, and possibly 2nm process nodes, will yield even more powerful SoCs and SoMs which could fundamentally change the limits of affordable, compact embedded systems. Furthermore, 3D chip stacking and chiplets emerging technologies are enabling new paths to system integration and customization.

As the Internet of Things (IoT) and the interconnection of embedded systems grow in their connectivity, more and more complex communication architectures must be developed. That includes injecting 5G modems for high speed, low latency connectivity, or adopting time sensitive networking (TSN) types for determining communication in Industry. It will also help us to see increased integration of security features in order to tackle with the growing cybersecurity issues of connected devices. Both energy harvesting and ultra-low-power design techniques have become important for IoT and sensor nodes that cannot be replaced often enough. That is driving new power management architectures and energy efficient processing techniques capable of powering long term deployed autonomous embedded systems. In the embedded space, the architectures of choice for open hardware are open hardware architectures like RISC-V. The open standards allow for more flexibility and customization of system design, which could also yield greater diversity and application specific embedded architectures. As the ecosystem around these open standards begins to mature, we should see increased adoption across other embedded applications.

## Conclusion

High performance edge computing driven by the rapidly increasing demand for powerful, efficient and secure computing solutions requires embedded system architectures with changing landscape considered. Embedded computing is seeing major changes across the board, with what's possible migrating rapidly down the path of integration of killer AI and machine learning capabilities, and into more sophisticated SoC and SoM solutions. Looking at the future, we can see that tomorrow, embedded systems will be key enablers of transformational technologies in a wide range of industries. But from a systems perspective, a Tcl should be an intermediate solution, as we look towards the more capable and efficient embedded solutions that ongoing trends towards heterogeneous computing, specialized AI accelerators, and new manufacturing processes will permit in the coming years.

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