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Research Article

Chiplet-Based Architecture for Next-Generation Vehicular Systems

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ABSTRACT

With technological advancements, semiconductors have become critical components for modern-day automotive systems. They are extensively used in various applications such as vehicular - safety, efficiency, connectivity, infotainment, and autonomous driving. The Automotive industry is experiencing a surge in demand for high-performance computing power and area-efficient systems. With physical, economic, technological, and design challenges, Moore's Law is reaching its practical limits. Also, supply chain issues during the COVID-19 pandemic have forced the automotive industry to search for alternative scalable design architecture such as chiplets, 3D stacking, and quantum computing. To this end, this work comprehensively surveys the scalable architecture for next-generation vehicular systems. It further analyzes and provides recommendations for chiplet-based architecture design for solving supply chain, area, power, and performance issues. It proposes chiplet-based vehicular system design by maximizing reuse, standardizing interfaces, and sharing resources.

Keywords: Automotive chiplet architecture, Next-generation vehicular systems, Autonomous driving, Fusion sensors, ADAS, Infotainment, Gem5, chiplet, Mcpat

1. Introduction

The exemplar shift in the automotive industry is driven by advancements in Machine Learning (ML), Artificial Intelligence (AI), and semiconductor technology. Modern vehicles are no longer mechanical constructs; they have evolved into complex cyber-physical systems with advanced electronics, sensors, and computational capabilities. This transformation is ushering in a new era of intelligent and connected vehicles, where the traditional boundaries between hardware and software are increasingly blurred. Industrial researchers have projected the semiconductor industry growth up to 1 trillion dollars, and 70% of it will come from automotive, computing, data storage, and wireless industries[1].

This dynamic shift in the automotive industry has increased the demand for semiconductor devices with high computing, high performance, multiple sensors, storage, AI, and ML accelerators. Modern-day automotives have a myriad network of computing, sensing, and processing engines. The automotive industry must keep up with demand by providing highly scalable, high-performance, and compute-intensive yet cost-effective semiconductor chips and devices. Fig.1 highlights the Society of Automotive Engineers (SAE) recommended self-driving evaluation timeline and its impact on electronics systems cost as % total car cost of the electronics devices. The automotive industry has projected ~30 to 35% growth in semiconductor utilization by 2030[2,3] with the arrival of fully automatic self-driving cars (levels 4 & 5), vehicle of everything (V2X)[4,5], and software-defined vehicles[6].

To support the increasing demand, research, and development, the semiconductor industry has developed approaches with application-specific electronic control units (ECUs) to a controller centralized design and customized Systems on chip (SOCs)[11]. However, these federated controller-based complex architectures have become challenging in maintenance, service, and cost[12]. Additionally, the hardware-software resources are not utilized with optimum potential and placed negative impact on the automotive systems' area, power, and performance.

Furthermore, the semiconductor industry has faced significant impacts from the global COVID-19 pandemic due to production shutdowns, supply chain disruptions, and bottlenecks[7,8]. The automotive industry was also badly affected by car production, chip shortages, increased prices, lack of inventories, and long waiting, which caused customers to choose pre-owned alternatives[9,10].

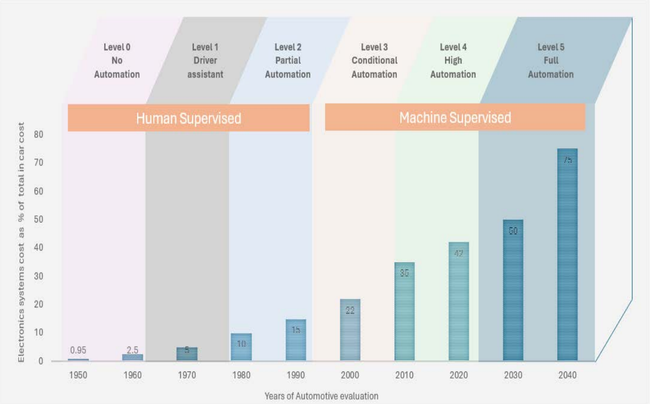


Figure 1: Highlights the evaluation of SAE levels and electronics systems cost as % total car cost.

To this end, this work presents the novel zone-based chiplet architecture for next-generation automotive systems. The performance evaluation results of the proposed zone-based chiplet architecture show high efficiency, optimum resource utilization by sharing, less power cost, and area performance compared to monolithic architectures. The chiplet-based architecture design also offers fast prototyping, heterogeneous core combination, standardized interconnect, and potential reduction in integration efforts.

2. Related Work

(Figure 2) Depicts the high-level semiconductor/electronics utilization in modern-day vehicular systems. This work has classified vehicular ECUs, sensors, and electronics networks into two broad categories for literature review.

1. Wired connection-based sensors and systems
2. Wireless sensors and systems

2.1. Wired connection-based sensors and systems

Based on state-of-the-art architecture designs, wired connection-based sensors and systems have been further classified into three subcategories.

1. Distributed Monolithic systems*:* Automotive systems have extensively used electronic control units (ECU) for specific task handling, such as powertrain management[13], advanced driver assistance systems (ADAS)[14], infotainment[15], and motion and environment perception sensors[16]. The distributed ECUs have enabled modular development and maintenance of hardware or software without affecting the rest of the system. However, due to the increased usage of ECUs, it has become challenging to architect, design, and network systems. It has led to complex systems design, interconnect/wiring management, and weight, increasing communication latency. It has led modern automotive systems design to explore alternative architectures that offer flexibility, scalability, and ease of integration[17].

2. Central controller/Hub-based systems: The automotive industry has adopted a centralized controller-based architecture system design to address the issues of a distributed ECUs-based monolithic approach. The centralized controller-based approach has a central high-performance compute and connection unit that coordinates and manages the communication between different ECUs. This approach reduces the networking/ wiring complexity, improves data processing, and offers over-the-air firmware software updates[13]. It is a resource-efficient system design since it consolidates the functionality to a central hub[12]. However, it makes the central hub a single point of failure and increases security vulnerability risk.

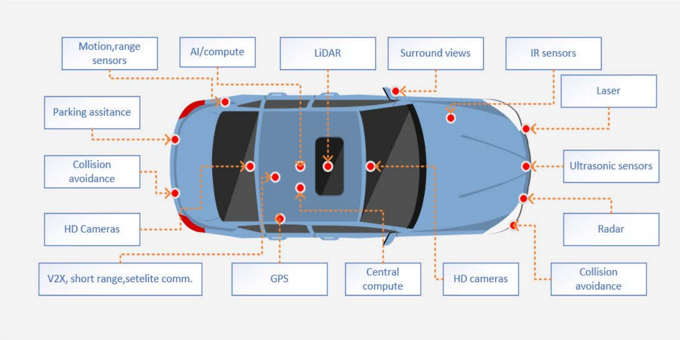


Figure 2: Depicts the electronics utilization in modern-day vehicular systems.

3. Zone-based systems: Zone-based architecture design for automotive ECUs is the most recent approach. The zones are defined based on the physical placement and usage of the ECUs and sensors within the vehicles; e.g., four controllers will be placed on each side of the vehicle to handle multiple ECUs and transactions within that region. It aims to achieve the balance between monolithic and central controller-based systems design by offering a more scalable, modular design that can handle growing expansion demands with less complex system design[17,18].

2.2. Wireless sensors and systems

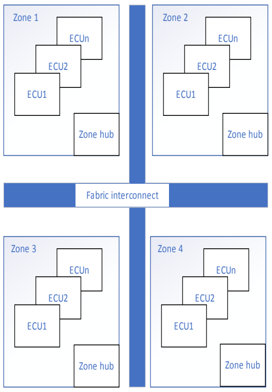
Vehicular communication has evolved significantly in recent years with the introduction and integration of Dedicated short-range communication (DSRC), Wifi, Bluetooth, 3G, Long Term Evolution (LTE) technologies, radio, and satellite communications[19]. This hybrid communication provides significant advantages for efficient, seamless, low latency, and high throughput data and information transfer[20]. Simultaneously, it opens multiple attack surfaces for modern attacks on automotive systems.

In summary, with changing demand and increased complex usage of semiconductors/electronics in vehicular systems, the industry has adopted different changes in system architecture. Few recent studies have also highlighted the utilization and challenges of Chiplet-based architecture for vehicular systems[11,12,21]. However, with the introduction of ML and AI-based accelerators, high-performance compute usages and the increased need for connectivity have become a challenging market for automotive semiconductor/systems vendors to keep up with. To this end, this work presents a novel zone-based chiplet architecture for next-generation vehicular systems. This approach provides optimum resource utilization with adequate communication requirements. Compared to monolithic vehicular electronics systems on simulation design, it reduces the hardware software resource requirements, area, power, and performance footprints. This work paves the way for next-generation chiplet-based system design researchers to explore the use of case-specific zoning, systems selection, and Chiplet and interconnect options.

3. Zone-Based Chiplet Architecture

(Figure 3) Shows the monolithic zone-based vehicular system. Each ECU inside the zone has its own l1 and l2 cache memory, processing unit, network, and GPIO connections. The connection between zones is through a system fabric interconnect. **(Figure 4)** Depicts the design of the proposed zone-based chiplet architecture. Each chiplet in the zone has a dedicated L1 cache for multiple CPU cores, whereas a dedicated shared L2 catch between all CPU cores within the zone.

Furthermore, each zone directly connects to the standard Network-On-Chip (NOC) interface via a dedicated zone hub. All inbound and outbound transactions must be routed through the zone hub, which checks access control and routes the transactions.



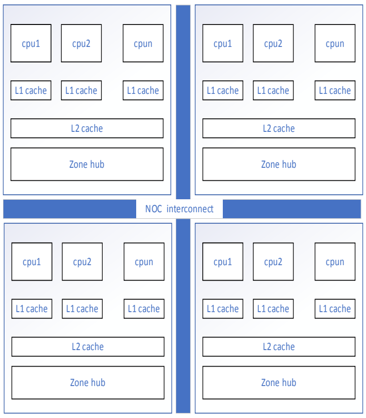


Figure 3: Zone-based Monolithic system architecture. **Figure 4**: Zone-based Chiplet system architecture.

The resource sharing, standard NOC interconnect, and zone-based access control validation help reduce the attack surface.

3.1. Implementation

The system design was simulated using gem5[22], and power, area, and timing results evaluations were performed using McPat[23]. 12 RISCV cores of ECUs with 4 ARM cores for zone hubs were instantiated for monolithic architectures. Each RISCV core operated at 1GHz, l1 cache of 32kb, and l2 of 32 kb with external cache coherent memory accesses and dedicated GPIO interrupts. 12 RISCV compute cores and 4 ARM-based zone hub cores were instantiated in gem5, with each computing core having a dedicated L1 cache of 32kb and a shared l2 cache of 32 kb; the network modelling was done by integrating Garnet with gem5.

3.2. Evaluation

The simulation results indicate the latency of the monolithic zone-based architecture versus that of zone-based chiplet architecture has less difference. However, the area and power saving are significant with chiplet-based system design. Furthermore, a chiplet-based zoning system isolates and limits potential attack surfaces. The standard NOC interconnect provides flexibility and a fast communication channel, reducing the interconnection complexity.

Table 1: Shows the simulation system setting, operating frequency and area information.

Core type	RISCV
Operating frequency	1GHz
Area for processor core	13.7mm2
Area for l1 cache	4.49mm2
Area for l2 cache	24mm2

Table 2: Depicts the cost, throughput, and latency for the proposed architecture.

Config	Cost	Throughput	Latency
Monolithic system	430	1.84E+02	29.240
Chiplet based system	129.534	1.95E+07	30.341

Cost is calculated by following equations 1 and 2.

$$\text{cost}=\text{costforeachDie}/\text{Yieldforassembly} \qquad (1)$$

$$\text{Yieldforassembly}=0.999\text{Numdie}*0.999999\text{Numg} \qquad (2)$$

Numdie is the number of dies made from a 300mm wafer and Numg is the number of gates on 7nm.

The simulation results indicate monolithic system cost is ~ three times higher than chiplet-based architecture.

3.3. Advantages

1. Scalability and Flexibility

- **Problem**: Traditional monolithic chip designs can be inflexible and difficult to upgrade or customize, limiting their ability to keep up with rapidly evolving automotive technology.
- **Solution**: Chiplet architecture allows for a modular approach where different functional blocks (chiplets) can be mixed and matched. This enables manufacturers to easily customize and upgrade components to meet specific requirements or adopt new technologies without redesigning the entire system.

2. Performance and Efficiency

- **Problem**: Increasing demands for high-performance computing in applications like ADAS, autonomous driving, and infotainment systems require significant computational power, which is challenging to achieve with traditional monolithic chips.
- **Solution**: Chiplets can combine different types of processors (CPU, GPU, AI accelerators) in a single package, optimizing performance for specific tasks. This leads to better overall system efficiency and performance, which is crucial for handling complex computations in real-time.

3. Cost and Yield Management

- **Problem**: Manufacturing large monolithic chips can be expensive, and yield rates can be low due to defects in the manufacturing process, leading to higher costs.
- **Solution**: Chiplets are smaller, easier to manufacture, and have higher yield rates. Defective chiplets can be discarded or replaced without wasting the entire chip package. This modular approach can significantly reduce manufacturing costs and improve overall yield.

4. Heat Dissipation and Power Efficiency

- **Problem**: As processing power increases, so does heat generation, which can lead to thermal management challenges and reduced power efficiency.
- **Solution**: Chiplet architecture can distribute heat generation evenly across the chip package. Additionally, power-efficient chiplets can be integrated, optimizing the system's power consumption and thermal characteristics, which is vital for electric and hybrid vehicles.

5. Integration of Advanced Technologies

- **Problem**: Integrating new technologies like AI, advanced sensors, and connectivity solutions into existing vehicle architectures can be complex and challenging.
- **Solution**: Chiplets enable the easy integration of advanced technologies. For instance, AI accelerators or specialized sensor processing units can be added as chiplets, enhancing the vehicle's capabilities without a complete system redesign.

6. Reliability and Redundancy

- **Problem**: Safety-critical applications in the automotive industry require highly reliable systems with redundancy to ensure consistent performance.
- **Solution**: Chiplet architecture can provide redundancy by allowing multiple chiplets to perform the same function. If one chiplet fails, others can take over, ensuring the system operates safely and reliably.

7. Time-to-Market

- **Problem**: Developing and validating new chip designs can take time and effort, delaying the introduction of new features and technologies.
- **Solution**: The modular nature of chiplet-based design speeds up development and validation processes. Pre-tested chiplets can be integrated into new designs quickly, reducing time-to-market for new automotive technologies.

8. Supply Chain Resilience

- **Problem**: Dependency on a single source for large monolithic chips can create supply chain vulnerabilities, especially in times of shortage.
- **Solution**: Chiplet architecture allows sourcing from multiple suppliers for different chiplets, enhancing supply chain resilience and flexibility.

3.4. Challenges and considerations

One of the key challenges in adopting the chiplet-based architecture is the transitioning and training for resources in adopting the change. The zone-based chiplet design requires the architects to know and understand the system-level usages to optimize the zoning and resource sharing. It will require software integration for distributed zone-based chiplets. Safe, time, and reliability constraints require a much tighter control of the component model and its semantics. This shift towards a more integrated architecture will decouple software design from the hardware platform design, providing opportunities for optimizing the architecture configuration and increasing extensibility, flexibility, and modularity. The industry needs the fabrication lab and infrastructure to support the increasing chiplet based designs.

4. Conclusion

The automotive industry is facing increased demands for vehicular features and functions that, intern require high-performance compute engines and complex networking. Gone are the days when semiconductor manufacturers took the time to develop individual solutions in-house. Chip makers are gearing up to combine multiple application-specific hardware-software stacks to support rapid market demands. This hybrid environment puts more pressure on design to adopt different hardware integration, scalable and area power efficient design development. Chiplet-based architecture tries to provide resource-optimized, power-efficient, and scalable solutions. On top of the proposed zone-based chiplet architecture helps in compartmentalizing/reducing potential attack surface, with security-aware interconnects and fast performance. The supported simulation results indicated ~3.5 area/ resource saving compared to a monolithic solution. Chiplet based architecture also helps in solving supply chain issues.

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