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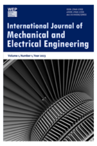

Overview of Chassis Domain Control System Architecture, Algorithms, and Verification Techniques

-- A Survey of Chassis Domain Control System Architecture, Algorithms, and Verification Techniques for Autonomous Vehicles

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ABSTRACT

This work systematically reviews the current status and development trends of autonomous vehicle chassis domain control systems across three dimensions: architecture, algorithms, and verification techniques. During the transformation toward intelligent vehicles, the limitations of traditional distributed electronic/electrical architectures in enhancing advanced autonomous driving capabilities have become apparent, prompting both industry and academia to shift focus toward the evolution of centralized domain control architectures. This study delves into the technical drivers and challenges underlying the evolution of chassis domain control systems from distributed to domain-centralized architectures. Building upon this foundation, it further explores the emerging trend toward zonal architecture. The study emphasizes hardware-software co-design strategies compliant with AUTOSAR standards. Through in-depth investigation and comprehensive evaluation, it conducts a holistic comparative analysis of traditional control methods—such as model-based predictive control and sliding mode control—alongside data-driven deep reinforcement learning strategies, examining their performance limits and application prospects within integrated vehicle chassis control systems. Finally, it systematically summarizes verification methodologies based on high-fidelity simulation (e.g., CARLA) and hardware-in-the-loop testing. This research aims to fill the current gap in integrating system-level architecture theory, providing a comprehensive technical blueprint and theoretical foundation for developing next-generation high-performance, high-safety intelligent chassis control systems.

KEYWORDS

Autonomous Driving; Chassis Domain Control; System Architecture; Model Predictive Control; Deep Reinforcement Learning; AUTOSAR.

1. INTRODUCTION

The automotive industry is undergoing a profound transformation centered on intelligence and automation. Against this backdrop, the chassis system—as the ultimate execution unit for vehicle motion—directly determines the safety limits, dynamic performance, and ride comfort of autonomous driving systems. However, the traditional distributed electronic/electrical (E/E) architecture—where individual chassis subsystems (e.g., anti-lock braking system (ABS), electronic stability program (ESP), electric power steering (EPS)) are controlled by independent electronic control units (ECUs)—can no longer meet the urgent demands of high-level autonomous driving for centralized computing power, functional integration, cost control, and rapid software/hardware iteration [1,2].This tendency to prioritize algorithms over architecture has led to significant progress in control algorithms within academic research, yet integration studies at the system architecture level remain insufficient. Particularly concerning key issues like standards for heterogeneous system integration, co-design of software and hardware, and functional safety assurance, no systematic theoretical framework or comprehensive solutions have yet been established [3]. To address these challenges, chassis domain control system architecture is undergoing a paradigm shift from distributed to centralized, ultimately evolving toward vehicle computing platforms and zonal architectures [4]. At this research stage, a high-performance Domain Control Unit (DCU) has been designed to integrate the functions of numerous distributed Electronic Control Units (ECUs), with its core responsibility being the coordinated processing of control logic integration across chassis subsystems.This shift not only introduces technical challenges in hardware integration, real-time communication, and functional safety but also demands novel control algorithms and comprehensive validation methods. While traditional approaches like Model Predictive Control (MPC) continue to evolve, data-driven intelligent control methods, exemplified by Deep Reinforcement Learning (DRL), demonstrate significant potential [5,6].Given the substantial economic costs and potential risks associated with testing autonomous driving systems in real-world environments, simulation-based validation methods—such as highly accurate simulation platforms like CARLA and CarSim, along with hardware-in-the-loop (HIL) testing approaches—have become critical steps in the development process of chassis domain control systems [7,8]. Although extensive research has been conducted globally in the field of autonomous driving chassis domain control, current work predominantly focuses on isolated aspects such as architecture, algorithms, or verification. There remains a lack of comprehensive reviews that integrate these three dimensions, systematically elucidating their intrinsic connections and developmental synergies [9,10].Furthermore, critical engineering issues such as the characteristics of underlying drive-by-wire actuators and their impact on overall domain control system performance, as well as the practical implementation of AUTOSAR standards in chassis domain control, remain under-discussed. Therefore, this work aims to establish a unified analytical framework. It systematically reviews the latest advancements in autonomous driving chassis domain control systems across architectural evolution, core algorithms, and validation methods. This framework clarifies the technological development path, compares and evaluates the strengths, weaknesses, and applicable scenarios of various technical solutions, and reveals the intrinsic connections and synergistic evolution patterns among different technical dimensions. The significance of this research lies in providing valuable references at both theoretical and practical levels to fill gaps in system-level architecture theory, promote deep interdisciplinary integration, and guide industry-wide technological breakthroughs and commercialization.

2. EVOLUTION OF CHASSIS DOMAIN CONTROL SYSTEM ARCHITECTURE

The transformation of automotive electronic/electrical architectures is fundamentally marked by the structural evolution of chassis domain control systems. This evolution signifies a shift from distributed to centralized architectures, progressing toward the formation of comprehensive vehicle computing platforms. This developmental trajectory clearly reflects the automotive industry's technological explorations in response to intelligent mobility challenges.

2.1. Distributed Control and Initial Integration

In traditional vehicles, core chassis subsystems long operated in isolation. Systems like ABS, ESP, and EPS each executed closed-loop control tasks through independent electronic control units (ECUs), establishing a signature distributed system architecture. Research during this period focused on optimizing individual subsystem performance and designing control algorithms [11]. As demands for overall vehicle dynamic performance (e.g., handling stability) increased, academia began exploring cooperative control between subsystems. For instance, Li Jing et al. designed a top-level integrated controller based on fuzzy PID to coordinate steering and yaw rate [12]. Wu Jianyong delved into the cooperative mechanism between four-wheel steering and direct yaw rate control, developing a two-layer integrated control system [13]. As shown in Figure 1, it is a schematic diagram of a steer-by-wire system.

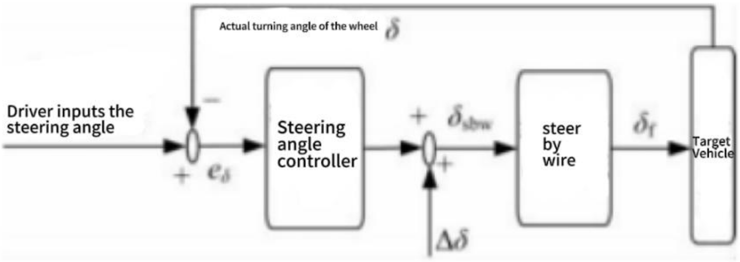

Figure 1. Schematic of the steer-by-wire control system

These studies laid preliminary theoretical foundations for subsequent domain control concepts, demonstrating the potential of integrated control to enhance vehicle performance under extreme operating conditions. However, their essence remained distributed ECU-based coordination, where upper-level controllers issued commands to execute on independent lower-level ECUs. This approach failed to achieve true unification at the underlying hardware and software architecture level, inherently suffering from limitations such as resource redundancy, communication bottlenecks, and high system complexity.

2.2. The Emergence of Domain-Centralized Architecture and Its Technical Challenges

To fundamentally address the bottlenecks of distributed architectures, domain-centric architectures emerged. Under this architecture, a high-performance domain controller (typically based on a heterogeneous system-on-chip, SoC) replaces multiple distributed ECUs. It is responsible for unified processing of control logic for multiple chassis subsystems (such as braking, steering, and suspension), vehicle state estimation, and execution of advanced autonomous driving functions [4,14]. This shift brings a series of new technical challenges and research hotspots:

In the hardware architecture domain, research focuses on selecting high-performance system-on-chip (SoC) solutions, which typically integrate ARM cores with FPGA/GPU technologies. Additionally, studies address appropriate allocation strategies between high-performance computing cores and safety island cores within heterogeneous computing architectures, aiming to design functional safety island solutions compliant with the highest functional safety levels (e.g., ASIL-D).The core challenge lies in ensuring the extreme real-time and reliability requirements for safety-critical functions like braking and steering.

Software Architecture Level: The AUTOSAR (Automotive Open System Architecture) standard serves as the cornerstone for achieving software-hardware decoupling and enabling software reuse [15]. For control functions with stringent real-time requirements, implementation approaches based on the AUTOSAR Classic Platform (CP) are a current research priority, with particular emphasis on deployment and validation on safety island cores. For complex perception-decision fusion functions requiring high computing power, exploring the application of the AUTOSAR Adaptive Platform (AP) represents a frontier topic. Related research addresses challenges such as hybrid deployment of AP and CP, communication performance optimization of middleware (e.g., SOME/IP), and the feasibility of applying service-oriented architecture (SOA) in real-time control domains [3].

2.3. Future Trends: Zonal Architecture and Vehicle Computing Platform

Domain-centric architectures represent the current mainstream development, but further centralization—zonal architectures and central computing platforms—is emerging as the future direction. Under zonal architectures, the vehicle's electronic/electrical layout is physically reconfigured.

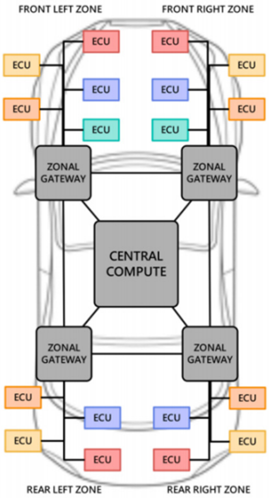

Figure 2. Physical Structure of a Zonal IVN (In-Vehicle Network) Architecture. The network structure undergoes physical reconfiguration, segmented into four independent zones: left front, right front, left rear, and right rear.

As shown in Figure 2, each zone gateway is responsible for connecting and controlling nearby actuators and sensors, communicating with the central computing platform via a high-speed backbone network (e.g., in-vehicle Ethernet) [12]. This architecture significantly reduces wiring harness length and weight, simplifies assembly processes, and enhances system scalability. Communication networks face unprecedentedly stringent requirements for real-time performance, reliability, and security, presenting core challenges in future research.

3. CURRENT RESEARCH STATUS OF CORE CHASSIS DOMAIN CONTROL ALGORITHMS

The core task of chassis domain control algorithms is to achieve coordinated optimization control of a vehicle's longitudinal, lateral, and vertical motions on an integrated hardware architecture, thereby comprehensively enhancing the overall performance of autonomous vehicles.

3.1. Advancements in Traditional Model-Based Control Methods

Model-based control methods dominate safety-critical chassis control due to their rigorous theoretical foundation and high interpretability.

Model Predictive Control (MPC): MPC explicitly handles constraints between system states and inputs, achieving multi-objective coordination through rolling optimization, making it the mainstream strategy for integrated chassis domain control. Research typically establishes high-fidelity vehicle dynamics models, integrating control actions from systems like Active Front Steering (AFS), Direct Yaw Rate Control (DYC), and active suspension to simultaneously optimize path-following accuracy, maneuverability stability, and ride comfort [15].Current research focuses include enhancing model accuracy, designing multi-objective cost functions that better reflect real-world driving demands, and developing efficient real-time solvers (e.g., explicit MPC) to address computational constraints of in-vehicle platforms.

Sliding Mode Control (SMC), as a nonlinear control technique, continues to attract significant attention in both academic and engineering circles due to its inherent robust resilience against parameter uncertainties and external disturbances. For instance, Wu Jianyong employed sliding mode control with a rotating sliding surface as a servo loop to enhance tracking accuracy and response speed for the reference slip rate [13]. Current research focuses on integrating intelligent methods or observer techniques to mitigate inherent chattering in sliding mode control and improve its adaptability in complex coupled systems.

3.2. The Rise of Data-Driven and Intelligent Control Methods

In recent years, data-driven methods represented by reinforcement learning (RL) and deep learning have provided a new paradigm for controlling complex systems characterized by high nonlinearity and model uncertainty.

Deep Reinforcement Learning (DRL): DRL excels by autonomously learning optimal control strategies through interaction data with the environment, without requiring precise environmental models. At the chassis control level, DRL applications include learning complex vehicle stability domain boundaries or replacing intricate numerical solution processes in real-time MPC optimization (e.g., learning MPC weight matrix adjustment strategies) [5]. Wang Yunze et al. systematically reviewed DRL applications in autonomous driving behavior decision-making, highlighting its trend toward permeating lower-level control systems [5]. The classification diagram of DRL algorithms in Figure 3 is crucial in academic reviews. It systematically organizes and presents the large family of DRL algorithms, laying the foundation for subsequent discussions on the applicability of different algorithms. This visualization method helps readers quickly establish a knowledge framework in this field.

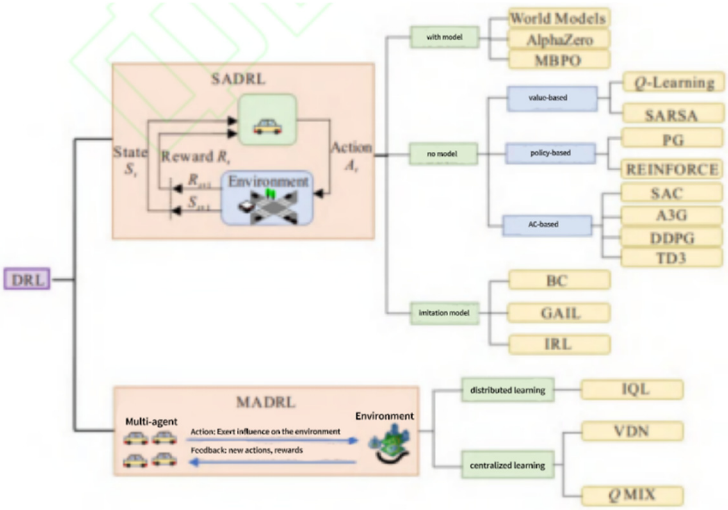

Figure 3. Classification of DRL Algorithms

However, DRL applications in safety-critical chassis control still face challenges such as poor policy interpretability, difficult-to-guarantee training convergence, and insufficient reliability in "long-tail scenarios." To address these, researchers have proposed various improvement methods. How Xiangkun et al. introduced adversarial robust reinforcement learning for trustworthy autonomous driving, enhancing policy robustness by simulating worst-case perturbations [6]. In his research on decision planning for hazardous scenarios, Xiangtong Shan combined deep imitation learning with DRL, utilizing expert demonstration data to guide agent learning and address the scarcity of hazardous scenario data [8].

Integration with Other Perceptual Modalities: In reinforcement learning-based visual navigation research, Goren employs variational autoencoders to reduce the dimensionality of high-dimensional visual inputs and introduces decision Transformers to capture temporal dependencies in historical states [13]. These innovations in enhancing algorithmic efficiency and robustness provide valuable insights for implementing DRL in underlying control systems requiring multimodal information fusion.As shown in Figure 4, it is a network structure diagram of a model (TransFuser) for autonomous driving.

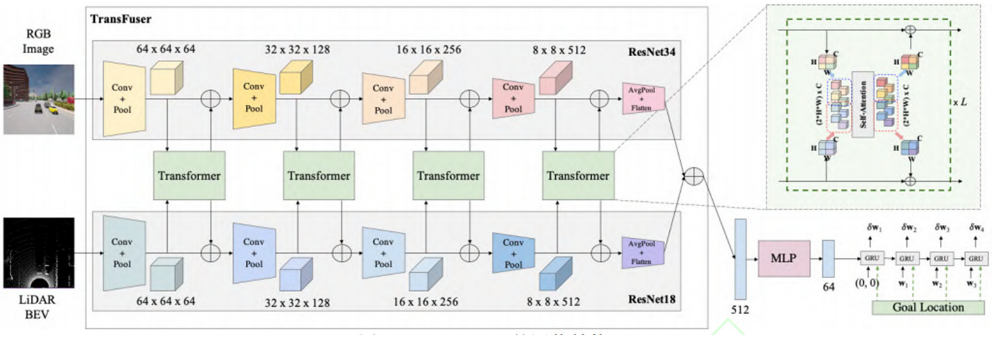

Figure 4. Network Architecture of TransFuser

4. CURRENT RESEARCH ON SIMULATION TESTING AND SAFETY VALIDATION

Conducting large-scale testing of autonomous driving chassis systems in real-world environments is impractical due to dual constraints of cost and safety. Consequently, simulation-based testing and validation have become essential stages in system development, establishing a comprehensive verification framework spanning Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), Hardware-in-the-Loop (HIL), and ultimately real-vehicle testing.

4.1. Simulation Testing Platforms and End-to-End Algorithm Validation

High-fidelity simulation platforms such as CARLA, CarSim, and Prescan are widely employed in autonomous driving algorithm development and testing [7]. Technologies like CARLA create highly realistic digital simulation environments capable of reproducing diverse climatic conditions, traffic elements, and intricate scenarios. This provides an exceptional training and verification platform for implementing end-to-end algorithms encompassing perception, decision-making, and control. Fu Guangming et al. conducted a systematic review of end-to-end autonomous driving algorithms simulated using CARLA, affirming simulation testing's significant advantages in cost reduction and coverage of extreme scenarios [7]. For chassis domain control systems, simulation testing not only verifies individual control algorithms but, more critically, evaluates the closed-loop performance and robustness of the entire control system within complex, dynamic environments. The simulation scenario diagram of CARLA in Figure 5 is valuable as it provides intuitive evidence of "high fidelity". It demonstrates the realism of the virtual environment, strongly supporting the argument that "simulation tests can cover extreme and dangerous scenarios" and enhancing the persuasiveness of the verification methodology section.

Figure 5. Driving scenario in the CARLA simulator, leveraging Unreal Engine rendering capabilities to generate realistic simulated environments via sensors

4.2. Hardware-in-the-Loop and Real-Vehicle Testing

Hardware-in-the-loop (HIL) testing establishes a critical link between virtual simulation and physical vehicles. During HIL testing, actual chassis domain controllers are integrated into the test system and interact with dynamically running vehicle dynamics simulations (e.g., models built on dSPACE or NI technology platforms) and simulated driving environments to form a closed-loop testing environment. This enables developers to validate controller functionality, performance, real-time capabilities, and interactions with other ECUs with high confidence in a laboratory setting—particularly for safety and reliability testing under fault injection and extreme conditions [13]. Wu Jianyong, Shan Zitong established HIL or Vehicle-in-the-Loop (VIL) test platforms in their research, reflecting the standardization and necessity of HIL testing within the chassis domain control development process [8,13]. Ultimately, systems thoroughly validated through simulation and HIL testing still require real-vehicle testing in strictly controlled test tracks or specific road environments to complete final performance calibration, extreme condition validation, and user acceptance assessment.

5. CONCLUSION AND RESEARCH OUTLOOK

This paper systematically reviews the latest research progress and challenges in autonomous vehicle chassis domain control systems across three dimensions: architecture, algorithms, and verification techniques. Research indicates that the transition from distributed ECUs to centralized domain controllers, coupled with the advancement toward zonal architectures, represents an inevitable development path to meet the requirements of high-level autonomous driving. However, during this transformation, critical issues such as scheduling heterogeneous hardware resources, developing high-real-time software middleware, and ensuring functional safety and cybersecurity within the system-level architecture must be thoroughly explored and resolved. At the algorithmic level, traditional methods like model predictive control continue to deepen, while data-driven approaches such as deep reinforcement learning demonstrate potential for handling complex uncertain environments. However, their reliability and interpretability in safety-critical scenarios remain obstacles that must be overcome before widespread adoption. In verification, testing systems based on high-fidelity simulation and hardware-in-the-loop have become the cornerstone for ensuring system safety and reliability. Future research will exhibit the following trends:

(1) Deep Integration of Architecture and Algorithms: Next-generation chassis domain control systems will emphasize co-optimization of software and hardware. Domain-Specific Architecture (DSA) concepts will permeate domain controller design to more efficiently support advanced control algorithms.

(2) Open Architecture and Standardization: The implementation of the AUTOSAR AP/CP hybrid architecture and the refinement of in-vehicle Ethernet communication protocols will drive further standardization of software-hardware interfaces, accelerating the formation of an industrial ecosystem.

(3) Balancing Intelligence and Safety: A core research focus will be developing "trustworthy" intelligent control algorithms that integrate the flexibility of data-driven methods with the interpretability and safety of model-based approaches.

(4) Closing the Loop Between Virtual Validation and the Real World: Leveraging digital twin technology to build higher-fidelity simulation models and enabling feedback iteration from virtual testing to real-world operational data will significantly enhance R&D efficiency and system reliability.

Integrating multidisciplinary knowledge, the autonomous driving chassis domain control system exhibits characteristics of a complex systems engineering project. It fuses cross-disciplinary applications from mechanical engineering, electronics, control theory, and computer science, reflecting the complexity inherent in systems engineering. Only through coordinated innovation across architecture, algorithms, and verification can we ultimately achieve high-performance, high-safety, and high-reliability intelligent chassis systems, enabling the large-scale commercial application of high-level autonomous driving.

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