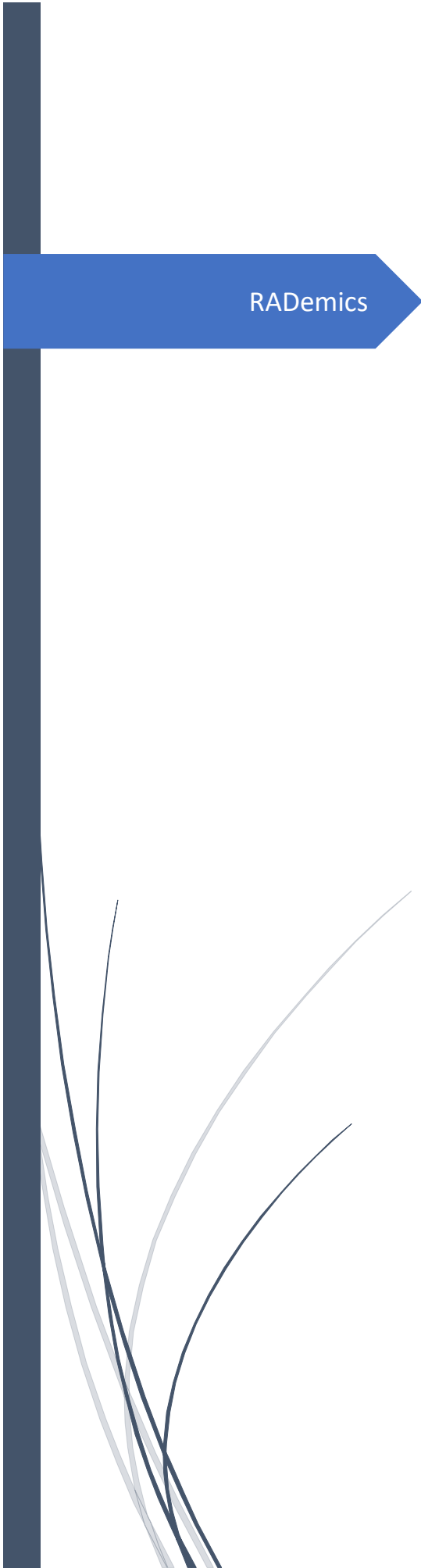




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Fusion of Machine Learning and Fuzzy Logic for Intelligent Control Systems in Autonomous Vehicles

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Abstract

The increasing complexity of autonomous vehicle operations necessitates intelligent control systems that can effectively handle uncertainty, non-linearity, and dynamic multi-task scenarios in real time. This book chapter presents a comprehensive exploration of hybrid control architectures that fuse machine learning with fuzzy logic to enhance decision-making in autonomous driving applications. The synergy between data-driven adaptability and rule-based interpretability enables these hybrid systems to manage complex environments while maintaining transparency and robustness. The chapter systematically addresses the taxonomy of neuro-fuzzy systems, fuzzy-Q learning, and deep fuzzy networks, emphasizing their adaptability across diverse driving tasks. Furthermore, it examines the integration of sensor fusion, contextual reasoning, and explainable AI into hybrid control loops, along with deployment strategies using embedded middleware frameworks such as ROS and AUTOSAR. Case studies in both urban and highway environments illustrate the performance of hybrid architectures in managing concurrent control objectives under real-world constraints. By unifying theoretical advancements with practical implementations, this chapter contributes to the advancement of safe, explainable, and adaptive autonomous vehicle control systems.

Keywords: Autonomous Vehicles, Hybrid Control, Machine Learning, Fuzzy Logic, Sensor Fusion, Explainable AI

Introduction

The evolution of autonomous vehicle technology has significantly transformed the landscape of intelligent transportation systems [1]. As vehicles transition from driver-assist to fully autonomous functionalities, the demand for intelligent control systems capable of operating in diverse and unpredictable environments has grown exponentially [2]. Traditional control strategies, which rely heavily on pre-programmed logic or mathematical modeling, often fall short in real-world scenarios characterized by uncertainty, noise, and dynamic interactions among various road users [3]. Autonomous vehicles are required to interpret complex traffic

environments, make timely decisions, and perform multiple tasks concurrently, such as lane keeping, obstacle avoidance, and speed regulation [4]. In such a context, the need for adaptive, data-driven, and interpretable control solutions has become increasingly critical. Hybrid control architectures that combine machine learning (ML) with fuzzy logic (FL) offer a robust alternative, enabling vehicles to learn from data while maintaining the ability to reason with uncertainty [5].

Machine learning techniques have demonstrated considerable success in perception and decision-making tasks within autonomous driving domains [6]. Deep neural networks, reinforcement learning, and probabilistic models enable vehicles to process vast amounts of sensor data and learn optimal policies from experience [7]. These approaches are often criticized for their black-box nature, making it difficult to interpret or validate the decision-making process [8]. This lack of transparency presents a major barrier in safety-critical applications, such as autonomous driving, where accountability, validation, and explainability are essential [9]. Machine learning models can exhibit limited generalization in edge cases or novel environments, leading to unreliable behavior in unanticipated conditions. These limitations necessitate the incorporation of additional control mechanisms that can enhance the robustness, transparency, and interpretability of intelligent decision-making systems without compromising adaptability and performance [10].

Fuzzy logic provides a powerful framework for modeling imprecision and reasoning in the presence of ambiguous or incomplete information [11]. Unlike crisp rule-based systems, fuzzy inference mechanisms allow the modeling of expert knowledge using linguistic variables and graded memberships, enabling autonomous systems to make decisions similar to human reasoning under uncertainty [12]. In the context of vehicle control, fuzzy logic has been successfully applied to applications such as speed control, lane merging, adaptive cruise control, and obstacle avoidance [13]. the scalability and adaptability of conventional fuzzy systems remain limited due to their reliance on hand-crafted rule bases and static membership functions [14]. As driving environments evolve rapidly, static fuzzy systems may lack the agility to respond effectively to unforeseen scenarios. Therefore, the combination of fuzzy logic with machine learning—creating adaptive hybrid systems—has emerged as a promising solution that addresses the shortcomings of both individual approaches [15].