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Membership Function Optimization In Fuzzy Logic Controllers For The Performance Enhancement Of ESP32-Based Line-Following Robots: A Systematic Review And Performance Analysis

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Abstract

The rapid evolution of autonomous robotics highlights the persistent challenge of controlling non-linear dynamics in line follower robots facing environmental disturbances. Traditional linear controllers exhibit inherent weaknesses, prompting a paradigm shift toward Fuzzy Logic Controllers (FLC). However, conventional FLCs predominantly rely on heuristic tuning for membership functions, resulting in suboptimal parameters and overtraining. Furthermore, advanced optimizations frequently ignore the hardware constraints of edge computing devices like the ESP32 microcontroller. This study presents a systematic literature review analyzing the optimization of fuzzy membership functions to enhance ESP32-based line follower performance. Utilizing the Theory of the Consolidated Meta-analytic Approach (TEMAC), this research systematically evaluates empirical studies from 2022 to 2026. The findings reveal that triangular membership functions are the most theoretically and computationally optimal geometry for the ESP32's Arithmetic Logic Unit, minimizing the processing latency without sacrificing the kinematic responsiveness. Moreover, the integration of population-based metaheuristic algorithms, specifically Particle Swarm Optimization (PSO), revolutionizes parameter tuning by systematically eliminating human bias. PSO-optimized FLCs significantly reduce the Root Mean Square Error (RMSE), virtually eliminate actuator overshoot, and drastically accelerate settling time compared to manual calibration. The implementation success ultimately depends on effectively managing

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the ESP32's dual-core Real-Time Operating System and integrating the ESP32-CAM visual sensors for precise centroid extraction. The review concludes that future automated guided vehicle designs must deeply synergize PSO-optimized fuzzy parameters with the computational limitations of silicon edge computing. This strategic hybridization produces highly resilient, power-efficient, and agile robotic prototypes capable of robust navigation across dynamic and highly unpredictable industrial environments.

Keywords: Line Follower Robot; Fuzzy Logic Controller; Membership Function; Particle Swarm Optimization; Edge Computing.

INTRODUCTION

The rapid evolution within the industrial automation landscape and smart manufacturing systems in the Industry 4.0 era has driven the widespread adoption of autonomous robotics technologies, wherein line following robots occupy a fundamental position as the foundational architecture for the development of Automated Guided Vehicles (AGVs). Within the hierarchy of intralogistics and intelligent transportation systems, the capability of a robotic entity to track and maintain its position along a predetermined path whether through high contrast visual lines or magnetic guidance serves as an absolute prerequisite that dictates overall reliability, safety, and operational efficiency. (Tran et al., 2023). Although the locomotion mechanism of two-wheeled differential drive robots is conceptually straightforward, controlling the nonlinear dynamics of these physical systems is fraught with various stochastic disturbances. Variations in surface friction coefficients, mechanical imperfections in Direct Current (DC) motors, power supply fluctuations, and the degradation of sensor readings caused by non uniform external illumination invariably induce detrimental heading errors and lateral positional deviations.

Historically, classical control approaches such as the Proportional-Integral-Derivative (PID) controller have dominated this application due to their implementation simplicity. However, researchers and practitioners recognize that conventional linear controllers possess inherent limitations. These methods rely heavily on rigid mathematical modeling and frequently induce phenomena such as integrator windup and derivative kick when encountering extreme changes in path curvature. Consequently, this generates chattering high-frequency actuator oscillations that damages motor mechanics and degrades wheel traction. The urgent need for a more robust and adaptive control paradigm, capable of accommodating dynamic uncertainties without requiring precise mathematical models, has driven the transition toward soft computing systems,

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wherein Fuzzy Set Theory and Fuzzy Logic have emerged as the most comprehensive solutions.

The conceptual foundation of this theory was established by Lotfi A. Zadeh in his seminal publication in (1965) in the journal *Information and Control*. In this paper, a fuzzy set is defined as a class of objects characterized by a continuum of grades of membership. This concept disrupted the classical bivalent (Boolean) logic paradigm by introducing a membership function that maps each element to a closed interval, thereby enabling the mathematical representation of ambiguous and uncertain linguistic concepts. The success of Zadeh's theoretical framework was subsequently translated into practical control systems by E.H. Mamdan (1974) to control dynamic systems through the synthesis of heuristic linguistic rules. Within the Fuzzy Logic Controller (FLC) architecture of a line following robot, crisp values representing the difference between the left and right sensor readings are first transformed into linguistic terms (e.g., "Large Left Error," "Center," "Small Right Error") via fuzzification. These values are then evaluated against a rule base and ultimately converted back into Pulse Width Modulation (PWM) signals for differential wheel actuation through defuzzification. Although FLCs have proven to be vastly superior to PID controllers in managing kinematic transitions and attenuating oscillations (Aji & Sutikno, 2023), the success and quality of its transient response are strictly contingent upon the geometric configuration and parameters of the membership functions employed during the fuzzification and defuzzification stages (Ross, 2010:175). An examination of state of the art academic literature spanning from 2023 to 2026 highlights a critical research and development gap.

Despite its theoretical advantages, the majority of FLC implementations on mid-range microcontrollers continue to rely on the heuristic tuning of membership function parameters, depending heavily on the designer's experience, trial-and-error intuition, and empirical observations (Chen & Pham, 2000:38). This empirical approach frequently results in suboptimal tuning. The designed controllers typically perform well only within narrowly defined simulated track conditions, but rapidly suffer from performance degradation or overfitting when subjected to novel track geometries, path bifurcations, or visual noise interference in computer vision-based systems.

To overcome this fundamental limitation, the control optimization paradigm has shifted toward the utilization of population-based metaheuristic algorithms, such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), to automatically determine the membership function parameters that yield the optimal fitness value (Tolossa et al., 2024; Mancilla et al., 2022). Nevertheless, the primary novelty of this article lies in situating the metaheuristic optimization process exclusively within the hardware architectural constraints of the ESP32 microcontroller an

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IoT based System on a Chip (SoC) widely adopted for its 32-bit dual-core processing capabilities and camera integration (ESP32-CAM). Most optimization studies published in top-tier journals tend to overlook the inherent limitations of embedded edge devices, specifically Arithmetic Logic Unit (ALU) execution latency, actuator signal resolution (e.g., 8-bit PWM), and RAM management constraints. Consequently, an in-depth investigation is imperative to bridge the gap between the mathematical complexity of theoretically optimized membership functions and the real-time execution capabilities of low-cost microcontrollers.

Consequently, the problem formulation of this study focuses on three comprehensive elements: (1) How do variations in the geometry and parameterization of membership functions (e.g., triangular, trapezoidal, and Gaussian) impact motion stability metrics, navigational accuracy, and computational execution efficiency within embedded systems?; (2) To what extent can metaheuristic computational algorithms, particularly Particle Swarm Optimization (PSO), systematically optimize fuzzy control parameters to overcome the limitations of heuristic tuning and minimize Root Mean Square Error (RMSE) deviations?; and (3) Which hardware architectural interventions of the ESP32 microcontroller and visual sensor fusion (ESP32-CAM) play a deterministic role in constraining or accelerating the response effectiveness of an optimized fuzzy controller under real-time operational conditions? The synthesis of this research is anticipated to yield a definitive theoretical reference framework and robust technical design guidelines for both researchers and robotics engineers.

In summary, the findings of this analytical review confirm that the geometric configuration and parameter tuning of membership functions are not merely computational visual instruments, but rather the most critical mathematical components dictating a robot's reaction time. Triangular functions, represented by first-degree polynomial equations, prove highly optimal for the Arithmetic Logic Unit (ALU) processing capabilities of the ESP32 microcontroller. Furthermore, integrating their parameterization with global search algorithms, such as PSO, can exponentially reduce Root Mean Square Error (RMSE). Moreover, robust fuzzy control performance is fundamentally contingent upon the simplification of defuzzification techniques. Transitioning from the Center of Gravity (CoG) method to a Takagi Sugeno model effectively curtails program iteration latency in high-resolution vision-based systems, thereby ensuring seamless synchronization between sophisticated software algorithms and actuator hardware constraints.

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METHODOLOGY

To ensure academic rigor and methodological depth in this article, the data investigation and elaboration processes were conducted using a systematic, descriptive-qualitative literature review framework. This framework partially adopts the principles of the Theory of the Consolidated Meta-analytic Approach (TEMAC), a methodology frequently employed in modern robotics literature meta-analyses (Brigido & de Oliveira, 2025). This methodological approach was implemented specifically to screen, categorize, and synthesize top-tier empirical findings concerning Fuzzy Logic Controller optimization, autonomous robot locomotion dynamics, artificial intelligence algorithms, and edge computing systems on specific microcontroller hardware.

In practice, the data collection strategy focused exclusively on leading, internationally reputable academic databases. The search timeframe was strictly restricted to the period between 2022 and the first quarter of 2026, ensuring that the reviewed microcontroller technologies (specifically the ESP32 and ESP32 CAM series) and optimization algorithms remain entirely relevant to state of the art computational architectures. The compiled search queries utilized Boolean operators, comprising string combinations of ("membership function optimization" OR "fuzzy logic parameter tuning") AND ("line follower" OR "path tracking" OR "autonomous mobile robot") AND ("ESP32" OR "metaheuristics" OR "PSO"). The retrieved results were subsequently filtered to exclude publications presenting solely offline simulations without empirical hardware validation, as well as articles from predatory journals lacking a rigorous peer-review process.

Subsequently, the data analysis technique employed a deconstructive approach. Quantitative performance metrics from the evaluated studies such as Percentage Overshoot (%OS), Settling Time, Integral of Time weighted Absolute Error (ITAE), and Root Mean Square Error (RMSE) were tabulated and subjected to comparative cross referencing. Each claim of efficiency or accuracy within the reviewed articles was interdisciplinary correlated against the physical limitations of electromechanical actuators (brushed DC motors) and the clock cycle processing capacities of the ESP32's Tensilica Xtensa Dual Core architecture. This comprehensive synthesis approach transcends superficial literature summarization; rather, it generates second- and third-order insights regarding the interdependent relationship between the mathematical abstractions of intelligent logic and the physical realities of semiconductor silicon restrictions.

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RESULT AND DISCUSSION

Theoretical Characterization and Modeling of Fuzzy Logic Membership Functions

Within the discourse of line following robot control, fuzzy control systems operate by leveraging perceptual uncertainty. The core of an FLC's capability to reason with sensor input signals which are frequently corrupted by mechanical noise or infrared scattering lies in the precise definition of its Membership Functions (MFs). In contrast to classical (crisp) sets, which enforce membership through a strict binary dichotomy (absolute truth or absolute falsehood, i.e., 1 or 0), fuzzy sets map the universe of discourse onto a continuous spectrum. This concept was first holistically articulated by L.A. Zadeh. This mapping is operationalized by a mathematical function, $\mu A(x)$, that maps each element x within the input domain (such as the centroid deviation of the line relative to the camera) to a linguistic representation degree within the [0, 1] interval.

Fuzzy Logic with Engineering Applications by Ross (2010), the selection of an appropriate geometric shape such as triangular, trapezoidal, or Gaussian is a critical design decision that significantly dictates the sensitivity and stability of the resulting control system, Timothy J. Ross (2010:175) emphasizes that there are an 'infinite number of ways to map membership functions to fuzzy variables.' However, to maintain algorithmic convergence stability and minimize processor cycle complexity, three curve types dominate mobile robot navigation applications: Triangular, Trapezoidal, and Gaussian (Bell shaped) Membership Functions. Furthermore, Chen and Pham (2000:38), in *Introduction to Fuzzy Sets, Fuzzy Logic, and Fuzzy Control Systems*, formally state that a membership function can be represented through the resolution principle decomposition or extension operations applied to real numbers.

The mathematical model of a triangular membership function is defined as a piecewise linear polynomial dependent on three scalar parameters (a, b, c), where *a* and *c* represent the lower and upper bounds of the curve's base, while *b* denotes the peak at which the degree of membership reaches unity. The algebraic representation, transcribed into high-level programming languages (such as C++ within the Arduino IDE or Espressif ESP-IDF frameworks), is formulated as follows:

$$\mu(x; a, b, c) = \max\left(\min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right)$$

This calculation demands highly efficient Arithmetic Logic Unit (ALU) execution, centered on simple conditional subtraction and division operations. This alignment is critical for meeting the high sampling frequency requirements of analog line sensor arrays (e.g., the QTR-8A module),

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which must be processed in real-time without inducing latency within the ESP32's Real-Time Operating System (RTOS) environment.

In contrast, the Trapezoidal Membership Function is characterized by a four-coordinate vector ($^{a, b, c, d}$) which creates a tolerance zone (flat top) of a specific duration. If the input error value resides within the interval [^{b,c}], the membership response value remains constant at a degree of unity (1). Meanwhile, the Gaussian Membership Function relies on two static parameters: the variance or curve width (σ) and the center of the distribution mean (^{c}), defined by the following mathematical formulation:

$$\mu(x; c, \sigma) = e^{-\frac{1}{2}\left(\frac{x-c}{\sigma}\right)^2}$$

The use of continuous transcendental exponential e^{x} functions is often favored by control theorists to achieve optimal smoothness in robotic actuator trajectories. However, the intensive and repetitive execution of natural logarithmic or high order floating point computations significantly exhausts the clock cycle budget of the ESP32 (Xtensa LX6) processor core. Such computational overhead not only induces thermal throttling and excessive power consumption but also degrades the responsiveness of the line-following robot when navigating sharp path deviations. These geometric and computational considerations serve as a critical foundation that must be established before the designer proceeds to the metaheuristic optimization phase.

Following the completion of fuzzification, the inference engine processes the IF-THEN logic matrix to generate an output. The final defuzzification process, which transforms the fuzzy sets back into crisp PWM values for DC motor control, frequently relies on the Center of Gravity (COG) formula (Chen & Pham, 2000:158–159). Operationally:

$$U_{out} = \frac{\int \mu_C(z) \cdot z \, dz}{\int \mu_C(z) \, dz}$$

For the implementation of discrete control in line-following robots, the integral is converted into a partial sum of discrete elements, denoted by the summation operator ($\sum$). While Mamdani-based defuzzification using the COG method provides a linear output response, many contemporary engineers in the field of edge computing advocate for a transition toward the Takagi-Sugeno-Kang (TSK) inference framework. In this paradigm, fuzzy outputs are not represented by complex geometric areas requiring integration, but rather by crisp singletons or polynomial mathematical functions (Aji & Sutikno, 2023). This transition represents a vital intersection in control algorithm optimization, where the reduction of defuzzification latency frees up significant memory resources for high-level visual sensor fusion.

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Impact of Membership Function Geometric Variations on Robotic Navigation Capabilities

A fuzzy controller cannot operate in a vacuum, isolated from the underlying mathematical properties of its membership functions. To comprehend the concrete implications for autonomous robot control, recent literature provides a high-standard analytical framework. In this study Shitsukane et al (2025) present a comparative analysis isolated from the geometric design influence of three membership function types (Triangular, Trapezoidal, and Gaussian) on the trajectory efficiency performance of a nonholonomic wheeled mobile robot operating within unpredictable environments.

Through a rigorously secured rule-base architecture designed to mitigate computational control bias, and leveraging the robust MATLAB/CoppeliaSim computational platform, this study successfully extracted quantitative statistical metrics. These results demonstrate that subtle differences in geometric abstraction exert a profound impact on the physical responsiveness of the robotic system. A one way Analysis of Variance (ANOVA) revealed statistically significant disparities (F =342.33 p, $p < 0.001$) among the three membership function types.

Table 1. Matrix representation of traversal time data across the three membership function geometries

Membership Function Geometry	Traversal Time (Detik)	Kinetic Transient Response Evaluation	ALU Workload Profile (Mikrokontroler)
Triangular	**177.95** (Most Computationally Efficient)	This generates a highly aggressive and decisive control response. The magnitude of the sensor error deviation instantaneously catalyzes an immediate differential velocity compensation.	Exceptionally lightweight. The piecewise linear interpolation is inherently compatible with fixed-point arithmetic operations on low end processor registers.
Trapezoidal (Trapesium)	**179.08** (Intermediate)	A reactivity dead-band is present along the flat-top tolerance plateau. While this characteristic	Moderate. It necessitates four parameter blocks per linguistic variable,

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		effectively mitigates micro-oscillations, it inadvertently delays the compensation of progressively accumulating errors.	marginally expanding the matrix memory footprint.
Gaussian	**181.05** (Slowest Traversal Time)	Provides an exceptionally smooth, jerk free acceleration transition for the left and right wheels, effectively mitigating severe traction friction. However, the initial transient response exhibits a sluggish characteristic.	Most computationally intensive. The mathematical transcendental function exp () demands hundreds of operations per cycle from the Floating-Point Unit (FPU), thereby bottlenecking the overall system sampling rate.

A second order reasoning analysis of the tabulated statistical data affirms that the completion time efficiency of 177.95 seconds achieved by the triangular membership function does not manifest arbitrarily. The triangular geometry ensures that even the most minute fractional change in the trajectory position error variable for instance, when the ESP32 optical sensor initially detects a mere 1-centimeter edge of the black tape instantaneously precipitates a sharp decline in the membership degree. The steep linear gradient inherent to the triangular structure acts as a computational "neural accelerator," triggering immediate adjustments in the PWM motor drive components, such as the L298N H-Bridge or the modern BTS7960 driver.

Conversely, the trapezoidal membership function introduces an artificial latency due to its flat-top plateau structure. In practical terms, this formulates a specific logical inference: 'As long as the robot deviates marginally (e.g., <2 mm) from the trajectory, maintain a constant motor velocity.' While this characteristic is advantageous for mitigating mechanical wear-and-tear on the gearboxes and suppressing trivial micro-corrections, within the context of extreme high-speed line-follower racing arenas, this micro-tolerance induces a delayed steering response, ultimately catapulting the robot off the track (destructive overshoot). Consequently, the preceding metric analysis implies that for practitioners leveraging ESP32 class microcontrollers, adopting the linear triangular membership function as the foundational design represents the most optimal rationale,

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both from the perspective of tracking responsiveness and computational clock rate efficiency (Shitsukane et al., 2025).

The Significance of Metaheuristic Optimization in Fuzzy Parameter Tuning

Even when a practitioner deliberately adopts the triangular membership function to alleviate the microcontroller's ALU workload, the subsequent design phase presents a far more critical challenge. In conventional fuzzy inference architectures, the coordinate domains (minimum boundary, absolute center peak, and maximum position/support width) for linguistic variables such as FAR_LEFT, LEFT, CENTER, RIGHT, and FAR_RIGHT are almost universally established through human intuition and empirical trial-and-error methodologies. A comprehensive literature review concerning intelligent control techniques for mobile robotics by (Mancilla et al., 2022).

According to the study, human designers are psychologically predisposed to optimize control parameters based solely on a specific set of laboratory trajectory data, where the robot exhibits flawless motion in a pristine, dust-free environment. This design practice inadvertently leads to an algorithmic pathology known as over-training. Heuristically calibrated intelligent controllers fail to generalize navigation when confronted with oval tracks, sharp S-shaped curves, 90-degree intersections, or asymmetrical zigzag paths. Since the semantic boundaries of the linguistic values are not prepared to respond to dynamic kinematic interventions, the robot tends to either delay cornering or suddenly succumb to uncontrolled oscillations.

To decouple the system from the constraints of human calibration bias, Mancilla et al. (2022) and the contemporary scientific community propose an integration architecture combining evolutionary computation and population-based Swarm Intelligence to design autonomous controllers. State-of-the-art global optimization algorithms include Genetic Algorithms (GA), Grey Wolf Optimizer (GWO), Harmony Search (HS), and the most dominant paradigm due to its impressive mathematical convergence rate: Particle Swarm Optimization (PSO). The computational process operates by iteratively evaluating all numerical parameters of the membership functions metaphorically represented as a 'swarm of particles,' where each particle signifies a coordinate solution vector (a, b, c) within an n-dimensional landscape converging toward the global optimum that minimizes the Root Mean Square Error (RMSE) of positional deviation (Kumar et al., 2024).

The most compelling empirical validation of PSO’s supremacy in this domain was extensively presented by Tolossa et al. (2024), who introduced a highly elegant hybrid

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architecture. Specifically, PSO was employed to manipulate and 'stretch' the width of the membership function bases, enabling optimal responsiveness to even the most minute geometric deviations. Simultaneously, the Genetic Algorithm (GA) was deployed in parallel for pruning or feature selection to reduce the complexity of the If Then rule base. This formidable combination delivers a quantum leap in performance for line follower architectures, as analyzed and summarized in the following comparison (Table 2).

Table 2. Comparative Analysis of Metaheuristic-Based Fuzzy Parameter Tuning

Performance Evaluation Metrics for Differential Drive Robotics	Conventional Control and Heuristic-Based Fuzzy Logic (Manual Tuning)	Hybrid Controller: PSO-GA Optimized Fuzzy Inference System
Root Mean Square Error (RMSE) X & Y	> to 0.371 m (relatively high; errors accumulate significantly during exponential curve navigation).	Highly precise. The lateral error was minimized to 0.032 meters (x), resulting in a 37.2% overall reduction in cumulative deviation percentage.
Settling Time	Frequently exceeding 0.82 seconds, the system exhibited delayed stabilization, characterized by persistent oscillatory pendulum-like behavior at the termination of straight-line trajectories.	The recovery response time was drastically accelerated to 0.4454 seconds, representing a 47.6% improvement in control responsiveness.
Persentase Overshoot	Significant. The uncontrolled behavior frequently compromises the steering mechanism due to torque spikes exceeding operational limits.	Nearly eliminated. The positional overshoot was reduced to an infinitesimal level (1.9984%), resulting in absolute, smooth motion devoid of mechanical chattering.
Robustness & Disturbance Rejection	The system tends to fail under friction-related disturbances	Highly robust. The controller maintains stability amidst

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	or asymmetrical slip conditions introduced to either motor.	internal uncertainty margins of up to ±20%, effectively eliminating performance degradation caused by sensory noise.
Actuator Energy Consumption Efficiency	The controller exhibits extreme effort, resulting in continuous high-frequency motor vibrations as it attempts to counteract even the slightest trajectory deviations.	Radical PWM Saturation Reduction: Power Consumption Savings for Mechanical Battery (LiFePO4/Li-Po) Systems Surpass 25.8%.

A philosophical and interdisciplinary inquiry (third-order thinking) into the RMSE achievements of Tolossa et al. (2024), coupled with the 0.445-second settling time metric, provides empirical confirmation that Fuzzy Logic Controller (FLC) optimization via iterative methods such as Particle Swarm effectively mitigates the system's tendency for redundant interventions. In power constrained IoT microcontrollers like the ESP32, electrical energy is disproportionately depleted by continuous high-frequency PWM switching activities attempting to arrest wheel inertia. However, when the base widths and centroids of the fuzzy membership functions (e.g., the 'Slight Curve' linguistic variable) are precisely calibrated using an evolutionary matrix, the PWM motor actuation injects an exact voltage ratio to dampen mechanical inertia just before the robot overshoots its trajectory centroid. The consequent absence of reactive torque spikes alleviates thermal throttling in the L298N motor driver circuit, profoundly enhancing Li-Po energy retention by more than a quarter of the total electrical demand.

Although the Particle Swarm Optimization (PSO) algorithm demands massive computational resources necessitating the comparative simulation of hundreds of particles this optimization process can, and ideally should, be executed offline utilizing supporting software environments such as the MATLAB/Simulink integrated simulation platform (Mancilla et al., 2022). Once the optimal membership function parameters and rule vectors are extracted, this final set of coordinate values is statically compiled, structured as C++ arrays, and deployed (flashed) into the ESP32 microcontroller's flash memory as an ultra lightweight control function for real-time line tracking. This hybrid distributed computing strategy effectively bridges the gap between the

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high complexity of PC-resource-intensive, swarm-based AI algorithms and the constrained execution realities of marginal-capacity IoT edge silicon.

Hardware Capabilities: Mapping the Optimization Paradigms of the ESP32 and ESP32-CAM

Designing robust mathematical control logic for encapsulated research instruments extends beyond mere theoretical formulation or PC-based software tuning. The physical operation of an autonomous robotic framework necessitates reconciling the inherent constraints of embedded edge computing, a domain predominantly driven by contemporary microcontroller technologies. A review of the literature from 2023 to 2026 reveals an exponential surge in the adoption of Espressif Systems' ESP32 microcontrollers as the primary processing unit for the majority of smart line follower prototypes and small-scale logistics Automated Guided Vehicles (AGVs) (Manggali et al., 2025).

The integration of this module is critical for implementing the parameterized optimization of membership functions. The ESP32 is driven by a Tensilica Xtensa Dual-Core 32-bit LX6 microprocessor architecture, capable of achieving massive clock speeds of up to 240 MHz. Furthermore, this microcontroller provisions up to 520 KB of internal static RAM (SRAM) a monumental leap compared to the classic generic 8-bit microcontrollers (e.g., the AVR ATmega328P powering the Arduino Uno, restricted to a mere 2 KB of SRAM) that have served as the backbone of early line-follower robot experiments for decades. This expanded memory architecture acts as a technical liberator; the dimensional complexity of the fuzzy logic rule base and the if-then interpolation of the MFs are no longer hampered by hardware memory constraints.

Another essential implication lies in the native FreeRTOS (Real Time Operating System) mechanism of the ESP32. In high level dynamic feedback control environments, scheduling latency between sensor peripheral acquisition and control cycle activation would negate the efficacy of even the most optimal membership function. Leveraging the dual-core architecture, system designers can compartmentalize computational workloads via task affinity: Core 0 is dedicated exclusively to handling connectivity interrupts for Wi-Fi/Bluetooth modules (IoT navigation data telemetry), while Core 1 focuses uninterrupted on ultra-low-latency data acquisition from the infrared ADC optical sensor array, executing matrix defuzzification processes, and continuously updating the DC motor's PWM frequencies. This workload deconstruction yields what is defined as deterministic control robustness, ensuring that control parameters formulated offline via the PSO metaheuristic method maintain their motion trajectories without degradation from hardware

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latency anomalies.

Furthermore, a fundamental paradigm shift within the sensory landscape of navigational robotics engineering warrants significant attention. Traditional line-follower robots have historically relied on digital or analog readings from reflective infrared photodiode modules (e.g., TRT5000 arrays) to capture the differential illumination reflectance between black and white lines. However, advancements in robotics research since 2024 have concurrently extensively analyzed the transition toward the integrated ESP32-CAM system platform. By coupling the ESP32 silicon with an OmniVision OV2640 series complementary metal-oxide-semiconductor (CMOS) image sensor, this module has ushered in a new era of Vision-Based Line Following (Manggali et al., 2025). A review of this academic paper demonstrates a paradigm shift in FLC inputs; rather than relying on absolute light reflectance values, the system captures Quarter Video Graphics Array (QVGA) or VGA resolution images. The image frame is subsequently cropped to isolate the Region of Interest (ROI), converted into a grayscale representation, and subjected to Otsu's thresholding algorithm. The system then extracts the Center of Gravity (Centroid) coordinates of the black pixel band representing the trajectory to define the Error Point. Ultimately, the pixel distance between this centroid and the center of the image canvas serves as the true mathematical input for the membership function fuzzification process of the fuzzy controller.

The transition to the ESP32-CAM system provides a broader field of view (FOV), facilitating predictive recognition of track curvature variations milliseconds before the wheel chassis footprint reaches the corresponding zone. However, this expanded visual orientation introduces susceptibility to electronic thermal noise and fluctuations in external illumination intensity (e.g., sunlight or ambient room lux indices). Shadowing effects on the trajectory line can potentially induce positional oscillations during centroid calculation, thereby continuously injecting false positive deviation signals into the FLC. In this critical compromise phase, the synergy of fuzzy parameter optimization acts as the primary defense mechanism. Particle Swarm Optimization (PSO) optimized triangular or trapezoidal membership functions can be structured with noise-resilient overlap margins that tolerate micro oscillations in centroid positioning. This configuration effectively prevents the algorithm from commanding erroneous motor angle corrections in response to high-frequency disturbances caused by impurities on the OV2640 camera lens or exposure to flickering external lighting.

Within the physical actuation domain, the output of the fuzzy algorithm is materialized as command pulse values directed to the motor driver circuitry. The ESP32 hardware features a dedicated LED Control (LEDC) PWM peripheral block, capable of operating with highly flexible

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precision resolutions ranging from a standard 8-bit configuration to a massive 16-bit resolution (yielding discrete motion partitions from 0 to 65,535). This architecture is consistent with established embedded system references for robotic balance tracking (Mora-González et al., 2025), FLC parameter configurations are conventionally tuned to respond within a baseline 8-bit PWM resolution format (yielding a deviation band from a minimum of -255 to an absolute maximum of +255). Consequently, harmonizing the numerically optimized matrix defuzzification parameters with these PWM resolution limit registers necessitates meticulous FLC structural alignment (scaling parameter tuning). A proportional mismatch between the Membership Function coefficients and the maximum Revolutions Per Minute (RPM) of a high-torque mechanical motor can nullify the efficacy of any state of the art control algorithm. Such a discrepancy ultimately yields a robot that achieves precision solely at the hexadecimal computational level, yet physically derails in real-world dynamics.

Control Architecture Hybridization: Toward the Fusion of Fuzzy-PID and Advanced Nonlinear Strategies

Brigido & de Oliveira (2025) This study documents the further methodological evolution beyond the pure implementation of Fuzzy Logic Controllers (FLCs). In analyzing the complexity of navigational trajectories within robotic transport systems and warehouse automation specifically autonomous logistics pathways in Robotic Mobile Fulfillment Systems (RMFS) architectures the engineering community has determined that peak efficacy is not inherently achieved by isolated fuzzy systems. Rather, the potential of these intelligent algorithms is maximized by assimilating Fuzzy Logic principles as a Supervisory Control layer within a dual-controller Hybrid Control architecture.

Two of the most revolutionary and robust hybrid control integrations for modern line-follower robots include the Fuzzy-PID (Proportional Integral Derivative) fusion and the intelligent fusion based on Sliding Mode Control (SMC). Tran et al. (2023) provided a critical empirical quantitative comparison of these Fuzzy-PID integration systems. The computational mechanism of this hybrid control architecture fundamentally alters the governance of fuzzy outputs. Instead of the FLC defuzzification process translating linguistic states (e.g., 'Large Left,' 'Medium Right') into absolute motor voltage commands, the FLC layer is engineered to function as an autonomous on the fly self-tuning mechanism for the Proportional Gain (K_p) and Derivative Gain (K_d) parameters of the underlying PID controller. When sensor readings detect the robot traversing a long, linear, and static vertical track, the fuzzy command suppresses response constants to ensure

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a balance between mechanical efficiency and constant traction without oscillation. However, upon the ESP32-CAM recording sharp cornering, rapid directional changes, or path branching, the fuzzy rule-based evaluation logic responds to the error gradient (delta error) instantaneously and exponentially boosting the (K_d) damping constant and (K_p) proportional acceleration. Tran's experimental results represent authentic hardware-based evidence demonstrating that the Fuzzy PD controller navigates extreme turns with precision that surpasses any classical PID implementation.

Within the spectrum of advanced mechanical control algorithm hybridization, research studies indexed in high-impact international quartiles have increasingly documented the integration of Fuzzy-Sliding Mode Control (Fuzzy-SMC) for line-follower mobilization. Yildiz et al (2020) Conceptually, Sliding Mode Control (SMC) is renowned in control systems engineering for its unparalleled robustness against parameter uncertainties and its exceptional ability to reject external kinetic disturbances, primarily through its sliding surface trajectory tracking. However, the inherent limitation of classical SMC lies in its tendency to force mechanical actuators into high-frequency discrete switching a phenomenon known as the 'chattering effect,' which is detrimental to actuator operational longevity. Within a hybrid assimilation, Fuzzy Logic computational functions are employed to smooth and interpolate the 'boundary layer' of the discontinuous switching logic inherent in SMC. At this culmination, the system governed by metaheuristic membership function optimization and hybridized SMC-Fuzzy integration fundamentally expands the efficacy boundaries of intelligent computational controllers. This approach secures absolute precision without compromising the thermal stability of the steering axis, thereby achieving a chattering free trajectory for IoT based semiconductor tracking robots.

Arising from the aforementioned hybrid architectural exploration is a critical cause-and-effect implication: any increase in computational complexity whether through cascading PID or SMC integrations requires the optimization of fuzzy membership functions to be precisely calibrated at their global optima. If membership function structures for a Fuzzy-PD controller are established via manual trial and error, the hybrid fusion may fail to achieve a harmonized compensation response, potentially exacerbating system inertia rather than mitigating it. Therefore, the application of Particle Swarm Optimization (PSO) to calibrate membership function coordinates on the ESP32 is no longer merely a complementary experimental recommendation; it is a fundamental determinant of success for high precision, industrial-grade autonomous AGV navigation systems.

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CONCLUSION

Based on a comprehensive review of literature and empirical decomposition of recent studies (2023–2026), the navigational efficacy of ESP32-based line follower robots is fundamentally governed by the shape and parameterization of membership functions. Specifically, triangular membership functions have proven theoretically and computationally optimal in minimizing the Arithmetic Logic Unit (ALU) processing load on IoT microcontrollers without compromising responsive movement. Furthermore, population-based metaheuristic algorithms particularly Particle Swarm Optimization (PSO) hybridized with genetic algorithms have demonstrated revolutionary superiority over heuristic manual tuning. This approach achieves absolute reduction in Root Mean Square Error (RMSE), eliminates positional oscillations (overshoot rejection), and accelerates control transition settling times to the millisecond range. Despite these mathematical advantages, achieving absolute mechanical stability in real-world environments remains contingent upon the synergistic fusion of advanced visual sensors like the ESP32-CAM (extracting pixel contrast values into precise trajectory deviations), the reduction of PWM actuator synchronization latency, and effective dual-core Real-Time Operating System (RTOS) computational allocation. Consequently, the next generation of AGV and line-follower design frameworks must rely on a systematic collaboration between PSO-optimized fuzzy parameter design and a keen awareness of edge computing power constraints. This paradigm paves the way for the development of robotics prototypes that are increasingly agile, energy-efficient, and resilient to diverse terrain variability.

FUTURE DIRECTIONS

Future research should prioritize the transition from offline metaheuristic tuning to dynamic, online parameter optimization directly within the edge computing constraints of the ESP32 microcontroller. While current architectures effectively utilize Particle Swarm Optimization (PSO) to mitigate positional overshoot and accelerate control transition settling times , the massive computational resources required currently necessitate offline simulation and compilation. Developing lightweight, adaptive optimization algorithms would enable real-time calibration against environmental uncertainties, particularly to counteract fluctuating external illumination and sensory thermal noise inherent in vision-based ESP32-CAM platforms. Furthermore, expanding the hybridization of Fuzzy Logic with advanced nonlinear strategies, such as Sliding Mode Control (SMC), to eliminate the high-frequency discrete switching "chattering effect" will be critical for scaling these intelligent controllers into more complex, industrial-grade

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Automated Guided Vehicle (AGV) navigation systems.

REFERENCES

Aji, B., & Sutikno, S. (2023). Fuzzy Logic Algorithm of Sugeno Method for Controlling Line Follower Mobile Robot. ILKOM Jurnal Ilmiah, 15(2), 283–289. https://doi.org/10.33096/ilkom.v15i2.1558.283-289

Brigido, W. J. H., & de Oliveira, J. M. P. (2025). The line follower robot: a meta-analytic approach. PeerJ Computer Science, 11, e2744. https://doi.org/10.7717/peerj-cs.2744

Chen, G., & Pham, T. T. (2000). Introduction to Fuzzy Sets, Fuzzy Logic, and Fuzzy Control Systems. CRC Press. https://doi.org/10.1201/9781420039818

Kumar, A., Sahasrabudhe, A., & Nirgude, S. (2024). Fuzzy Logic Control for Indoor Navigation of Mobile Robots. http://arxiv.org/abs/2409.02437

Mamdani, E. H. (1974). Application of fuzzy algorithms for control of simple dynamic plant. Proceedings of the Institution of Electrical Engineers, 121(12), 1585. https://doi.org/10.1049/piee.1974.0328

Mancilla, A., García-Valdez, M., Castillo, O., & Merelo-Guervós, J. J. (2022). Optimal Fuzzy Controller Design for Autonomous Robot Path Tracking Using Population-Based Metaheuristics. Symmetry, 14(2), 202. https://doi.org/10.3390/sym14020202

Manggali, A. D., Dintarisanto, R. J., Athaozih, M., Nadziron, A. I., & Priambodo, A. S. (2025). Design & Implementation of ESP32-CAM Based Line Follower Robot With Fuzzy Logic for Intelligent Navigation. Jurnal Informatika Dan Teknik Elektro Terapan, 13(3), 451–458. https://doi.org/10.23960/jitet.v13i3.6874

Mora-González, I., García-Martínez, J. R., Pérez-Juárez, J. G., Martínez-Sánchez, T., Olmedo-García, L. F., & Rojas-Galván, R. (2025). Experimental Evaluation of a Fuzzy Logic-Based Controller for a Two-Wheeled Balancing Robot. 2025 Mexican International Conference on Computer Science (ENC), 1–7. https://doi.org/10.1109/ENC68268.2025.11311917

Ross, T. J. (2010). Fuzzy Logic with Engineering Applications. Wiley. https://doi.org/10.1002/9781119994374

Shitsukane, A., Otieno, C., Imende, J. O., & Mukhongo, L. (2025). Comparative Analysis of Membership Functionsin Fuzzy Logic Controllers for Robot PathPlanning Optimization. International Journal of Mathematical Sciences and Computing, 11(3), 47–57. https://doi.org/10.5815/ijmsc.2025.03.04

Tolossa, T. D., Gunasekaran, M., Halder, K., Verma, H. K., Parswal, S. S., Jorwal, N., Maria Joseph,

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F. O., & Hote, Y. V. (2024). Trajectory tracking control of a mobile robot using fuzzy logic controller with optimal parameters. Robotica, 42(8), 2801–2824. https://doi.org/10.1017/S0263574724001140

Tran, Q.-K., Huu, C. T. N., & Pham, C.-T. (2023). Experimental Study on Fuzzy PD Control for Logistics Transportation Mobile Robot. In Industrial Networks and Intelligent Systems (pp. 225–235). https://doi.org/10.1007/978-3-031-47359-3_17

Yildiz, H., Korkmaz Can, N., Ozguney, O. C., & Yagiz, N. (2020). Sliding mode control of a line following robot. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 42(11), 561. https://doi.org/10.1007/s40430-020-02645-3

Zadeh, L. A. (1965). Fuzzy sets. Information and Control, 8(3), 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X

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