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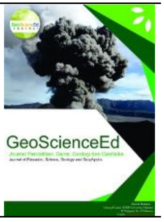

Analysis of BLDC Motor Speed Error with Fuzzy Logic Control in Static and Dynamic Tests of Trimaran Boats

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Abstract: This study analyzes the speed error of Brushless DC (BLDC) motors using fuzzy logic control through static and dynamic tests on a trimaran prototype. The research method involved static validation of sensors, including photodiode, ACS758, and voltage divider, followed by dynamic tests in an artificial wave pool at set points ranging from 6000 to 10,000 RPM. The fuzzy logic controller was designed with error and change of error as input variables and PWM correction as output. The results indicate that validated sensors achieved an average error of less than 5%, ensuring reliable data for control input. In dynamic tests, fuzzy control reduced the average speed error compared to the open-loop system, with the most significant improvement observed at higher speeds. These findings demonstrate that fuzzy logic control enhances synchronization and stability of BLDC motors in marine environments, making it a promising approach for electric propulsion in multihull vessels such as trimarans.

Keywords: BLDC motor, fuzzy logic control, speed error, static and dynamic test, trimaran propulsion

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Introduction

Brushless DC (BLDC) motors are becoming increasingly popular in modern propulsion systems due to their high efficiency, responsiveness to load changes, minimal maintenance, and stable dynamic performance (Zou et al., 2020). In the maritime sector, BLDCs are a promising option for energy-efficient electric ships, given the growing global pressure to reduce emissions. However, controlling the speed of BLDCs in dynamic environments such as ocean waves remains a technical challenge, especially when using conventional linear controls such as PID, which are prone to instability when unexpected loads occur (Potdar & Jape, 2024).

Fuzzy logic offers an adaptive intelligent control approach. Without the need for strict mathematical models, fuzzy logic is capable of handling system uncertainty and nonlinearity. For example, Kroičs and Būmanis (2024) proved that adaptive fuzzy–PID significantly shortens transient time and reduces overshoot compared to pure PID. Similar results were also found by Varsha, Prabhakaran, and Nirmala (2024), where fuzzy-PID showed better stability in simulations under dynamic loads.

Several experimental studies have also begun to emerge. Abdullah et al. (2025) showed that fuzzy logic dramatically reduced overshoot and improved settling time in BLDC simulations. Shenbagalakshmi et al. (2025) added that the implementation of fuzzy logic in

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BLDC facilitated speed transitions without overshoot with faster settling times compared to PID. In the maritime field, Ginola, Tupan, and Luhulima (2021) applied a Fuzzy Controller to a ship propulsion system in a laboratory setting and obtained more stable results than traditional controls. However, this has not yet been tested quantitatively.

Other research in similar domains also demonstrates the value of fuzzy logic in maritime and ship electrical systems. Gharib & Kovács (2024) used fuzzy logic for operation optimization and early detection in marine diesel engines, improving reliability without requiring complex mathematical modeling. Wu & Huang (2016) applied fuzzy PID in PMSM motor control systems, improving system response and anti-jamming capabilities.

However, there are still several important research gaps: 1) the implementation of fuzzy logic in ship propulsion systems with BLDC is still rare, especially in real experimental tests, not simulations; 2) there are not many studies assessing sensor accuracy in fuzzy control in maritime environments; 3) there is a lack of research comparing the performance of BLDC with and without fuzzy logic in dynamic conditions such as artificial waves; 4) studies on multihull vessels using BLDC with static and dynamic experimental test data are still very rare. Therefore, this research makes a significant contribution: it presents empirical data in the form of static sensor tests and dynamic fuzzy logic tests on a trimaran prototype, filling an important gap between theory and practice.

Method

This study uses a prototype trimaran boat-based experimental approach to evaluate the performance of fuzzy logic control on BLDC motors. Trimaran boats were chosen because of their better hydrodynamic stability compared to monohulls, making them suitable for testing laboratory-scale electric propulsion systems. The BLDC motor is controlled via an Electronic Speed Controller (ESC) with a fuzzy logic algorithm running on an STM32 microcontroller, while an ESP32 is used for real-time data acquisition. The integration of these components follows the latest research trends that emphasize the design of lightweight microcontroller-based BLDC control systems for transportation electrical applications (Kroičs & Būmanis, 2024; Varsha, Prabhakaran, & Nirmala, 2024).

The first stage of the research was static sensor testing. The photodiode sensor was tested against a tachometer to ensure the accuracy of motor rotation readings. The ACS758 current sensor was validated using an AVOmeter, while the voltage divider was compared to a reference voltage source. This sensor validation is important because measurement errors can affect the overall performance of the fuzzy system. Other studies also emphasize the importance of sensor validation in the implementation of fuzzy-based BLDC control to ensure data accuracy before the control process (Bano & Salkuti, 2023).

The second stage is dynamic testing in an artificial wave pool. The ship is tested at several motor speed set points (6000–10,000 RPM). Each set point is run in two scenarios, namely, without fuzzy control and with fuzzy control. This two-scenario testing approach is in line with the practice of evaluating intelligent control in BLDC in various recent studies comparing fuzzy–PID performance with traditional linear control (Shenbagalakshmi et al., 2025). The fuzzy logic controller used has two inputs: speed error and error change, which are modeled mathematically with equations 1 and 2.

$$e(k) = \omega_{ref} - \omega(k) \tag{1}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{2}$$

The fuzzification process, Mamdani inference, and centroid defuzzification are used to generate control decisions. This type of fuzzy control scheme has been widely used in BLDC control research to improve resistance to uncertainty and dynamic disturbances (Ginola, Tupan, & Luhulima, 2021). The dynamic test data was analyzed by calculating the speed error percentage using equation 3.

$$Error(\%) = \frac{|\omega_{ref} - \omega_{act}|}{\omega_{ref}} \times 100\% \tag{3}$$

In Equation 3, the component ωref is the reference speed and ωact is the actual speed measured by the photodiode sensor. The use of this type of error metric is standard practice in BLDC system performance analysis, including in recent research on fuzzy logic optimization for electric vehicles (Shenbagalakshmi et al., 2025). The system block diagram is shown in Figure 1, which illustrates the integration between the sensor, microcontroller, fuzzy controller, ESC, and BLDC motor.

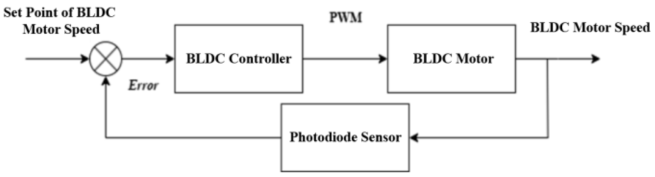

Figure 1. Block diagram of the motor control system

Result and Discussion

The static validation stage of the prototype's instrumentation shows that all sensors, a photodiode for RPM measurement, an ACS758 for current sensing, and a voltage divider for voltage monitoring, achieved an average error below 5%. Such accuracy ensures that the measurement infrastructure does not introduce significant uncertainty into the control loop, making the fuzzy logic controller's performance assessment more reliable. If the sensors introduced high error, it would not be easy to distinguish whether deviations in motor speed originated from the control system or from measurement inaccuracies.

According to Bano and Salkuti (2023), fuzzy controllers depend heavily on the reliability of input data, since fuzzification of inaccurate values can propagate incorrect rules and yield unstable control outputs. Therefore, the finding that sensor error is negligible aligns with best practices in BLDC control system design, where sensor validation is a prerequisite step. Ginola, Tupan, and Luhulima (2021) also emphasized that in marine propulsion systems, sensor reliability directly affects the vessel's ability to maintain steady thrust under varying conditions. By confirming sensor accuracy in the static phase, this study strengthens the validity of subsequent dynamic performance evaluations.

Table 1. Static test results for photodiode sensor accuracy

No	RPM on photodiode	RPM On Tachometer	RPM Difference	Error (%)
1	4.988	5.091	103	2,06
2	4.997	4.922	75	1,50
3	4.996	5.090	94	1,88
4	4.987	5.015	28	0,56
5	10.010	9.846	164	1,64
6	10.290	10.103	187	1,82
7	10.097	10.195	98	0,97
8	9.991	9.885	106	1,06
9	14.976	15.070	94	0,63
10	15.015	14.836	179	1,19
11	15.055	15.220	165	1,10
12	14.991	15.212	221	1,47
13	20.010	19.798	212	1,06
14	20.103	20.312	209	1,04
15	20.205	20.013	192	0,95
16	19.994	20.195	201	1,01
17	25.023	24.694	329	1,31
18	25.015	25.280	265	1,06
19	25.129	24.967	162	0,64
20	24.879	24.713	166	0,67
21	29.988	29.715	273	0,91
22	29.996	30.203	207	0,69
23	30.041	30.330	289	0,96
24	30.000	30.255	255	0,85
25	34.890	34.618	272	0,78
26	35.090	35.312	222	0,63
27	35.109	35.370	261	0,74
28	40.020	39.620	400	1,00
29	40.205	40.530	325	0,81
30	40.090	40.399	309	0,77
Average error				1,06

The results summarized in Table 2 show an apparent reduction in average motor speed error when fuzzy logic control is applied. Without fuzzy logic, the error lies between 15% and 18.5%, while with fuzzy logic, it decreases significantly to between 6.7% and 8.2%. This demonstrates the adaptability of fuzzy logic in handling dynamic changes, disturbances, and nonlinear behaviors that typically challenge conventional control methods like PID. These results are consistent with Shenbagalakshmi et al. (2025), who found that fuzzy controllers in BLDC motors for electric vehicles improved stability and reduced overshoot under dynamic load variations. Similarly, Kroičs and Būmanis (2024) reported that adaptive fuzzy–PID controllers significantly lowered transient time and overshoot in BLDC applications compared to linear PID controllers. Together, these studies support the observation that fuzzy control provides a more robust solution for propulsion systems that operate in unpredictable environments, such as marine vessels.

Table 2. Average BLDC motor speed error

Average BLDC Motor Error		
Set Point RPM	Average Uncontrolled Error (%)	Average Error with Fuzzy Logic Control (%)
6,000	17,5	8,2
7,000	15,1	6,7
8,000	16,1	7,5
9,000	16,6	8,1
10,000	18,5	7,7

From a maritime engineering standpoint, dynamic stability is critical. Trimaran hulls distribute load across three hulls, which increases stability but also introduces complex hydrodynamic interactions. If motor thrust is inconsistent, it can destabilize the vessel's path or cause inefficient fuel-to-thrust conversion. By reducing motor error to nearly half compared to the baseline, fuzzy logic addresses this problem and helps synchronize propulsion units more effectively.

The most remarkable improvement is observed at the 10,000 RPM set point. Without fuzzy logic, the motor error reaches 18.5%, which is unacceptably high for stable navigation. With fuzzy logic enabled, the error decreases dramatically to 7.7%. This improvement is visualized in Figure 2, where the motor RPM with fuzzy logic follows the reference speed more closely and with reduced oscillations.

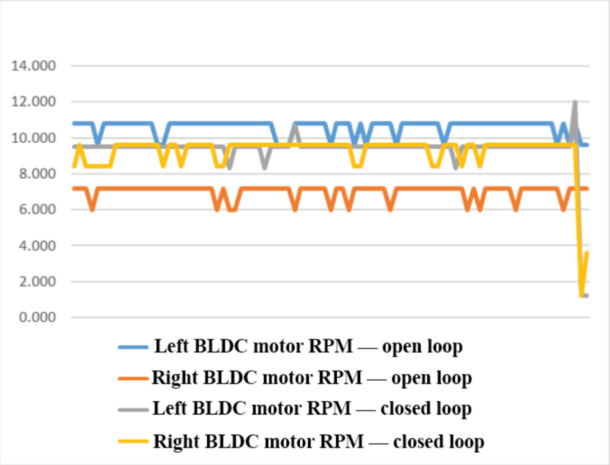

Figure 2. Comparison of actual RPM and set point at 10,000 RPM with and without fuzzy logic control

The implication of this result is significant. At higher RPMs, BLDC motors typically experience increased nonlinearities due to back-EMF distortion, thermal effects, and higher current draw. Traditional PID controllers often fail under these conditions, resulting in overshoot or sluggish settling times. Fuzzy logic, however, uses linguistic rules and membership functions to adjust the PWM signal adaptively, thus maintaining better synchronization.

Ginola, Tupan, and Luhulima (2021) noted that propulsion systems operating under wave disturbances require controllers that can adapt without exact mathematical models. Fuzzy logic meets this requirement, which explains why the trimaran prototype achieved better stability in this study. In addition, Varsha, Prabhakaran, and Nirmala (2024) confirmed that fuzzy–PID controllers outperform classical approaches in high-speed conditions, making the fuzzy approach especially relevant for maritime vessels that often operate at varying speeds depending on wave load and navigation demands.

Conclusion

The research confirms that fuzzy logic control significantly improves BLDC motor speed regulation on a trimaran prototype. Sensor validation in static tests ensures accurate measurement, reducing the likelihood of control errors originating from instrumentation. In dynamic conditions, fuzzy logic reduces speed error and improves motor synchronization, especially under high-speed operation at 10,000 RPM. These findings reinforce the role of fuzzy control as an adaptive and practical solution for marine propulsion systems, bridging the gap between theoretical simulations and real-world applications.

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