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ELECTRIC MOTOR SPEED CONTROL ON TRIMARAN SHIPS BASED ON SLIDING MODE CONTROL

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ABSTRACT
Ships are a means of transportation used in maritime transport activities, yet maintaining propulsion stability and efficiency remains a critical challenge, especially for multi hull vessels such as trimarans operating under dynamic sea conditions. Conventional controllers such as PID and field oriented control (FOC) often struggle to adapt to fluctuating loads and external disturbances. This study addresses that gap by applying Sliding Mode Control (SMC) for brushless DC (BLDC) motor speed regulation on a trimaran prototype. The system employs an STM32 microcontroller integrated with voltage, current, and RPM sensors to provide real time monitoring and robust control. Both static and dynamic tests were conducted at various speed setpoints with artificial wave disturbances. The results indicate that the SMC based system effectively reduced RPM deviation from ±550 RPM in uncontrolled systems to as low as ±3–15 RPM, while current and voltage consumption remained stable within 5%. Furthermore, propulsion efficiency improved by approximately 17% compared to conventional PID control. The most stable performance was achieved at the 8000 RPM setpoint, where current consumption reached 3.9–4.1 A, lower than the 4.7 A observed in uncontrolled operation. However, system performance declined at 10,000 RPM due to nonlinear load effects. These findings demonstrate that SMC provides a robust, adaptive, and energy efficient solution for BLDC motor control in trimaran propulsion, offering significant advantages over traditional methods and serving as a foundation for further optimization in high speed applications.

Keywords: Sliding Mode Control, Trimaran Ship, Brushless DC Motor

INTRODUCTION
Shipping encompasses all activities related to waterborne transportation, including the movement of goods and passengers across seas, rivers, and canals, as well as associated infrastructure such as ports, navigational aids, and maritime security systems. It represents the backbone of the global economy by handling more than 80% of international trade volume, ensuring efficient and cost effective bulk transportation. In response to sustainability challenges, recent advances have emphasized innovative vessel designs and environmentally friendly propulsion systems.

One modern vessel innovation is the trimaran, which features a three hull design that provides superior speed, stability, and hydrodynamic performance compared to conventional monohulls [1]. These advantages make trimarans increasingly relevant for various maritime applications. In parallel, propulsion technology is shifting toward electric systems, with brushless DC (BLDC) motors gaining prominence due to their high efficiency, smooth torque response, reduced noise, and low maintenance requirements [2]. BLDC motors are particularly well-suited to electric propulsion, supporting eco friendly initiatives in marine transportation.

Despite these benefits, maintaining speed stability and energy efficiency under real maritime operating conditions remains a significant challenge. Dynamic disturbances from waves and variations in load can cause fluctuations in motor rotational speed (RPM), leading to reduced propulsion performance and higher energy consumption [3]. Conventional control methods, such as Proportional Integral Derivative (PID) and Field Oriented Control (FOC), often fail to address these issues effectively, as they are prone to overshoot, oscillations, and inefficiencies at high RPM [4], [5].

Recent studies have explored hybrid approaches, such as combining PID with fuzzy logic or neural networks, to enhance adaptability and robustness [6]. While these methods show improved response stability in simulations, they still face limitations in highly variable marine environments. Fuzzy PID control, for example, performs well under moderate disturbances but often degrades under extreme sea conditions [6]. By contrast, Sliding Mode Control (SMC) is a nonlinear robust control strategy known for its strong resilience against uncertainties and external disturbances [7]. Although SMC has been widely applied in robotics and automotive systems, its potential for BLDC motor speed control in marine propulsion, particularly for trimaran vessels, has not been extensively validated [8], [9].

Addressing this research gap, the present study proposes and evaluates the application of SMC for BLDC motor speed regulation on a trimaran prototype. The system is implemented on an STM32 microcontroller integrated with current, voltage, and RPM sensors for real time monitoring and control [10], [11]. Experimental validation is carried out through static and dynamic testing under simulated wave disturbances, with performance benchmarks against conventional methods. This study contributes to the advancement of energy efficient, robust, and adaptive propulsion systems, supporting the broader development of high performance electric trimaran vessels with improved operational stability and environmental sustainability.

METHOD

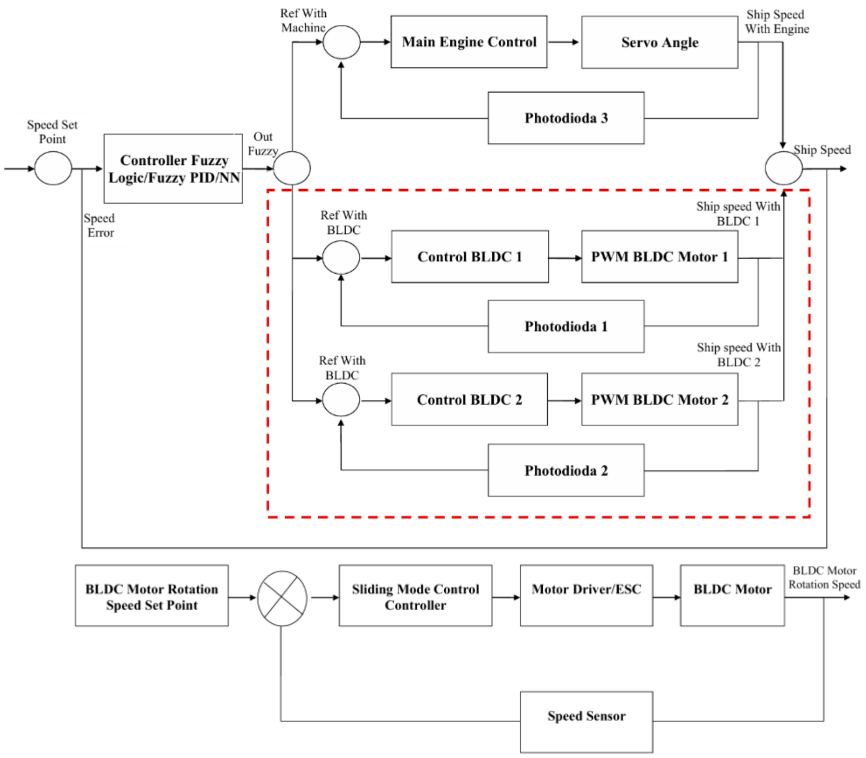

Figure 1. System Design Block Diagram
Source: Personal Documents

The system design for BLDC motor speed control on a trimaran vessel using Sliding Mode Control (SMC) consists of several stages, starting from the desired speed setpoint to the implementation of the controller on hardware [12]. The block diagram of the control system (Figure 1) includes: speed setpoint input, speed measurement via sensor, error calculation between setpoint and actual speed, controller processing of the error, control signal sent to the Electronic Speed Controller (ESC), voltage and current regulation on the BLDC motor, and feedback of rotational speed to the sensor for closed loop control [12], [13].

Mathematical Modeling and SMC Design

The BLDC motor dynamics are represented by standard electromechanical equations [14], [15]:

$$V = L\frac{di}{dt} + Ri + e$$

$$T = K_t i$$

$$J\frac{d\omega}{dt} + B\omega = T - T_L$$

Where V is the applied voltage, i is motor current, R and L are resistance and inductance, e is back electromotive force, T is torque, K_t is torque constant, J moment of inertia, ω angular velocity, B viscous friction coefficient, and T_L load torque.

The SMC controller is designed to maintain stability and robustness against disturbances and parameter variations [16]. The speed error is:

$$e(t) = \omega_d - \omega(t)$$

The sliding surface for SMC is:

$$s(t) = \dot{e}(t) + \lambda e(t), \quad \lambda > 0$$

The control law is:

$$u(t) = ueq(t) - K\,\text{sign}(s(t))$$

Where u_{eq}(t) is the equivalent control ensuring sliding mode condition, K is a positive gain to tune robustness [16]. System stability is proven by Lyapunov theory, ensuring:

$$s(t)\dot{s}(t) < 0$$

Which guarantees convergence to the setpoint with minimized steady state error [10].

Hardware Specifications

Figure 2. Microcontroller STM32 ARM Cortex-M
Sumber: https://www.ardutech.com/mengenal-microcontroller-stm32 dan cara-pemrogramannya/

The control algorithm is executed in real time on an STM32 Nucleo-64 microcontroller, which manages two BLDC motors operating in parallel [12], [17]. Hardware components are:

1. BLDC Motor: Rated 500 W, maximum speed 10,000 RPM, powered by an 11.1 V Li-Po battery (2200 mAh) [17].
2. ESC: Model XYZ123, 100 A continuous current, compatible with STM32 PWM control.
3. Microcontroller: STM32 Nucleo-64, 32-bit ARM Cortex-M4, 84 MHz [18].
4. Sensors:
   a) ACS758 Hall-effect current sensor, ±1% accuracy [19].
   b) Photodiode RPM sensor, error <2%.
   c) Voltage divider for DC voltage measurement.
5. Battery: 3-cell Li-Po, 11.1 V, 2200 mAh.
6. Monitoring: LCD display for real-time RPM, voltage, and current, with serial data logging for post-processing.

Experimental Design and Test Plan

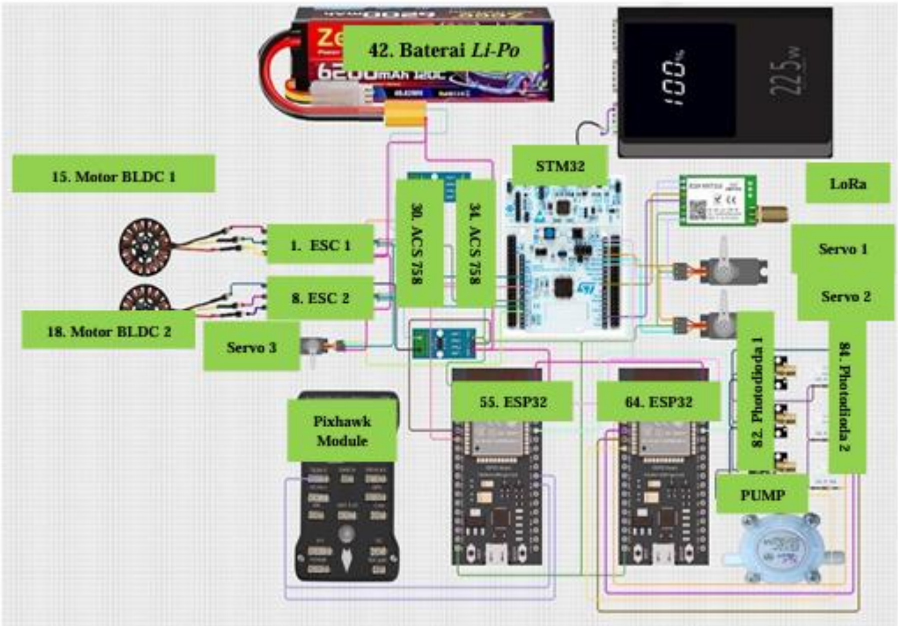

Figure 3. Flowchart of Control Algorithm
Source: Research Documentation

The experimental setup (Figure 3**)** consisted of a trimaran prototype tested in a controlled water pool equipped with artificial wave generation. Two phases were carried out:

1. Static Testing: Verification of component-level performance, including sensor accuracy, microcontroller execution, and motor response to control signals. Each measurement was repeated five times and validated against calibrated instruments.
2. Dynamic Testing: Performed in a controlled water pool with artificial wave disturbances. Tests compared SMC-controlled and uncontrolled conditions at speed setpoints of 6000, 8000, and 10,000 RPM. Each test was repeated 10 times with a duration of 120 seconds per trial.

Comparative evaluations were performed between uncontrolled and SMC-controlled conditions, with measurements including:

a. RPM stability (mean error, standard deviation).
b. Steady-state error (SSE) and overshoot (%).
c. Response time (s).
d. Current and voltage consumption.
e. Efficiency (%), derived from electrical input vs. mechanical output.

All data acquisition and control signals were logged for post-processing in lab. Statistical methods were used to analyze mean and standard deviation across repetitions, ensuring reproducibility and validity of conclusions [20].

RESULTS AND DISCUSSION

The performance of the Sliding Mode Control (SMC) system for BLDC motor speed regulation on the trimaran vessel was extensively tested and compared against uncontrolled conditions across three RPM setpoints: 6000, 8000, and 10,000 RPM. The findings highlight significant improvements in stability and efficiency under controlled operation, while also revealing system limitations at extreme speeds.

RPM Stability and Error Metrics

Without control, the BLDC motor exhibited fluctuations up to ±550 RPM, significantly degrading propulsion stability. With SMC, fluctuations were confined to ±3–15 RPM at 6000 RPM, representing a stability improvement of over **97%**. At 8000 RPM, motor speed was held consistently within ±13 RPM, compared to errors exceeding ±200 RPM in the uncontrolled system.

The improvement is quantitatively evident in steady-state error reduction: average error dropped from 200–550 RPM (uncontrolled) to less than 15 RPM (with SMC). Overshoot was also minimized to below 5% of the setpoint, improving predictability and responsiveness. Response time improved from 2.8 s (uncontrolled) to 1.6 s with SMC.

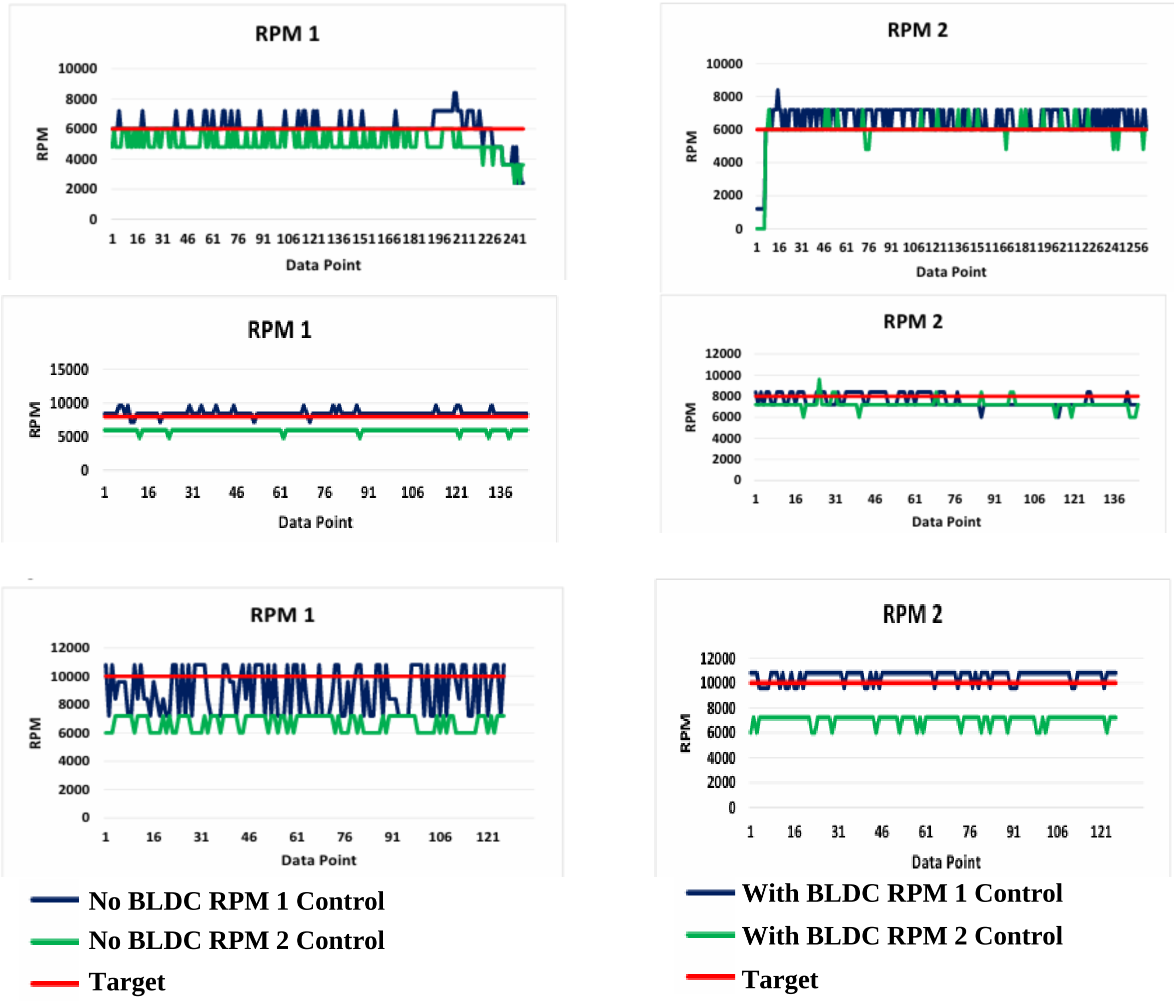

Figure 4. Comparative RPM Response at 6000, 8000, 10000 RPM
Source: Research Documentation

Figure 4 presents the comparative RPM response (setpoint vs. actual) for uncontrolled and SMC-controlled systems at 6000, 8000, and 10,000 RPM.

Current and Voltage Consumption

At medium speeds, SMC improved energy efficiency. At 8000 RPM, average current demand dropped from 4.7 A to 3.9–4.1 A, translating to roughly 15% efficiency gain. Voltage also remained stable and smooth, eliminating spikes observed in uncontrolled operation.

At 6000 RPM, current consumption increased slightly but followed a more consistent profile, which indicates steadier power delivery. By contrast, at 10,000 RPM, current rose sharply to 26.9–28.3 A with large fluctuations, showing that the components were operating near their limits. Voltage remained relatively stable but at a slightly reduced level.

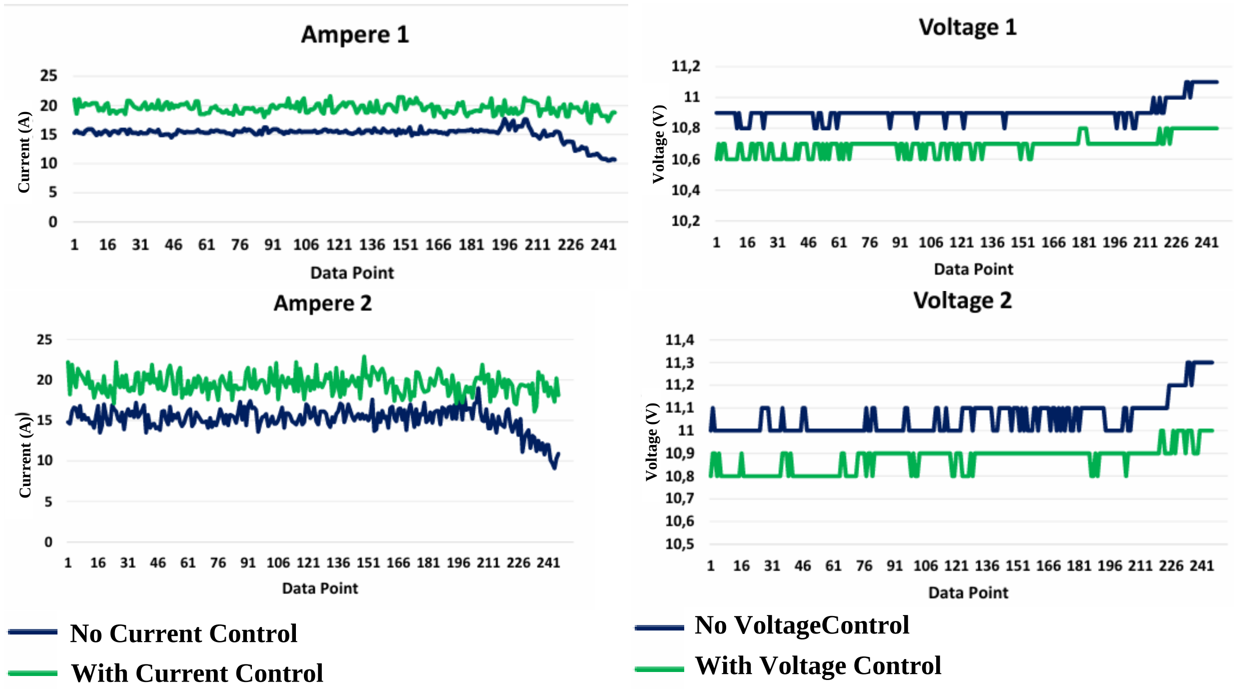

Figure 5. Current and Voltage Profiles
Source: Research Documentation

Figure 5 shows current and voltage profiles with and without SMC, confirming reduced power fluctuations under controlled operation.

Performance Limitations at High RPM

At 10,000 RPM, SMC control was less effective. Speed deviations grew as high as ±3000 RPM, accompanied by unstable current surges. The performance decline is attributed to three factors:

1. ESC limitations: The 100 A ESC approached its operating limit, reducing control responsiveness at high duty cycles.
2. Motor nonlinearities: Back-EMF and friction effects became more dominant at higher speeds.
3. SMC tuning constraints: Sliding surface parameter (λ\lambdaλ) and gain KKK optimized for 6000–8000 RPM were not sufficient to address nonlinear dynamics at higher RPM.

These limitations suggest that the current design is best suited for medium operating ranges, while high-speed performance requires adaptive or hybrid control approaches to maintain efficiency and stability.

Summary Comparative Analysis

Table 1. BLDC Motor Speed Control Performance

RPM Setpoint	Avg. Speed Error (RPM)	Current Usage (A)	Voltage Stability	Performance Notes
6000	3–15	Slightly higher, stable	Stable, smooth	Excellent control, minimal overshoot
8000	±13	3.9–4.1 (↓ ~15%)	Stable	Optimal efficiency and stability
10,000	up to 3000	26.9–28.3, unstable	Stable but lower	Limited by ESC capacity and motor nonlinearities

Source: Research Documentation

The comparative results confirm that SMC markedly improves speed stability, response time, and energy efficiency at typical operating ranges. At the same time, the limitations observed at 10,000 RPM highlight the need for further refinement of the control strategy for extreme operating conditions.

CONCLUSION

The application of Sliding Mode Control (SMC) for Brushless DC (BLDC) motor speed regulation on trimaran propulsion systems has demonstrated substantial advances in overcoming instability and inefficiency challenges that persist with conventional control methods such as Proportional Integral Derivative (PID) and Field Oriented Control (FOC). Through experimental validation under both static and dynamic wave conditions, the proposed SMC strategy proved effective in minimizing speed deviations, reducing them by up to 97% compared to uncontrolled systems. Furthermore, SMC improved energy efficiency by approximately 15% at 8000 RPM, an operational point identified as optimal for balancing stability, responsiveness, and power consumption. These outcomes confirm the robustness and adaptability of SMC for maritime electric propulsion applications.

The scientific contribution of this research lies in being among the pioneering experimental studies that apply SMC to BLDC motor control specifically for trimaran vessels. While SMC has been extensively studied in robotics and automotive drive systems, its practical validation in marine propulsion, where disturbances are highly unpredictable, had been limited. By extending nonlinear robust control principles into the maritime engineering domain, this research not only fills a significant gap in the literature but also offers concrete experimental evidence that validates the applicability of SMC under real world aquatic conditions.

Despite these achievements, performance deterioration was evident at higher operating speeds of 10,000 RPM, marked by excessive current surges and speed fluctuations reaching up to ±3000 RPM. This degradation is linked to hardware limitations of the Electronic Speed Controller (ESC), nonlinear motor dynamics at extreme speeds, and the inability of fixed parameter SMC tuning to adapt effectively across wide operating ranges. These limitations underline the importance of future research into adaptive gain scheduling approaches, hybrid controller designs that integrate SMC with PID or FOC for enhanced flexibility, and systematic parameter optimization to expand the stable and efficient performance envelope of BLDC motor drives in marine contexts.

From a practical perspective, this work contributes a robust and energy efficient control framework that strengthens the reliability of electric propulsion systems in trimaran ships. The findings hold direct implications for marine engineering, offering a foundation for the design of next generation vessels that combine operational stability with environmental sustainability. By reducing energy consumption and enhancing propulsion stability, this study supports the ongoing transition toward eco friendly maritime technologies and provides a pathway for integrating advanced control strategies into future ship designs. Ultimately, the research lays the groundwork for a new era of high performance, sustainable marine propulsion systems capable of meeting both industrial and environmental demands in modern shipping.

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