JOURNAL DIGITAL TECHNOLOGY TREND
E-ISSN: 2963-8143, P-ISSN: 2963-9190
Volume 4 Number 1, June 2025, pp 27-35.
HTTPS://DOI.ORG/ https://doi.org/10.56347/jdtt.v4i1.271.

Design and Optimization of a Low-Cost DC Electric Motor for IoT-Based Smart Device Applications

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ABSTRACT
The rapid development of Internet of Things (IoT) technologies has intensified the need for compact, cost-effective actuators that can be seamlessly integrated into smart devices such as home automation systems and portable robotics. This study presents the design, construction, and optimization of a low-cost direct current (DC) electric motor using readily available materials, including copper wire, an iron core, and neodymium magnets. A series of experiments were conducted to evaluate the influence of coil turns, magnet strength, input voltage, and pulse-width modulation (PWM) duty cycles on torque, rotational speed, and efficiency. Results demonstrated that a configuration with a 100-turn coil, a 0.4 Tesla magnet, and a 9 V power input achieved a rotational speed of 160 RPM with an efficiency of 34%, confirming suitability for low-power IoT devices. Finite Element Analysis (FEA) was employed to validate and refine the experimental design, showing a 20% improvement in magnetic flux density and a close correlation with measured torque values. Furthermore, the motor was integrated with an ESP32 microcontroller, enabling precise speed regulation and remote operation via Wi-Fi and MQTT protocols, as demonstrated in a prototype smart fan application. With a total manufacturing cost of under $5, the proposed motor design offers a scalable and affordable solution for resource-constrained environments, addressing barriers to widespread IoT adoption in developing regions. The findings highlight the potential of combining simple construction methods with digital control and simulation tools to create efficient, accessible, and IoT-compatible actuators that support ongoing advancements in smart device technology.

ARTICLE HISTORY
Received 28 April 2025
Accepted 20 June 2025
Published 30 June 2025

KEYWORDS
Dc Motor; Iot Integration; Low-Cost Actuator; Finite Element Analysis; Pwm Control.

1. Introduction

The Internet of Things (IoT) has significantly reshaped the technological landscape by enabling networks of interconnected smart devices for purposes such as home automation, environmental monitoring, and robotics (Atzori *et al*., 2010; Gubbi *et al*., 2013; Rathore *et al*., 2016). Central to the operation of these systems are actuators that must be both affordable and compact, with direct current (DC) electric motors serving as a primary solution for mechanical actuation (Hughes & Drury, 2013). Despite their utility, commercially available motors often present challenges related to cost and complexity, particularly for small-scale IoT deployments in developing regions (Rao, 2019). Addressing these barriers, this research focuses on the design and optimization of a low-cost DC motor based on accessible materials and straightforward construction methods, inspired by practical engineering projects and experimental documentation. The working principle of the motor is grounded in electromagnetic induction, where a current-carrying coil exposed to a magnetic field produces rotational motion (Griffiths, 2017). By refining critical parameters such as the number of coil turns, magnetic field strength, and input voltage, it is possible to achieve performance characteristics suitable for smart device applications, including automated fans and window blinds. Integration with IoT platforms is facilitated through pulse-width modulation (PWM)

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control, allowing for precise speed regulation and remote operation via microcontrollers like the ESP32 (Sedra & Smith, 2020). To further enhance design accuracy, finite element analysis (FEA) is utilized to model magnetic field interactions and predict motor performance, thereby reducing the need for iterative prototyping (Zienkiewicz *et al*., 2005).

The importance of optimizing DC motors for IoT applications is underscored by ongoing demands for efficient, reliable, and economically viable electric propulsion. Brushless DC (BLDC) motors, in particular, are valued for their high efficiency, low maintenance, and ease of digital control, making them especially relevant for devices with strict constraints on size, weight, and power consumption (Ismail & Elnady, 2019; Alibek *et al*., 2024; Anshory, 2017). Their ability to deliver precise speed and torque control is essential for ensuring the responsiveness and reliability of smart devices (Apribowo *et al*., 2021; Fang *et al*., 2015). Furthermore, the inherent cost-effectiveness and high power density of DC motors support their widespread adoption in a range of IoT applications (Ismail & Elnady, 2019; Alibek *et al*., 2024). Recent research has highlighted the role of advanced control strategies and optimization algorithms in improving motor performance. Fuzzy logic controllers and evolutionary algorithms, such as the JAYA algorithm, have been implemented to enhance control precision and operational efficiency, ensuring that DC motors can meet the varied demands of modern smart devices (Apribowo *et al*., 2021; Yuan *et al*., 2024). These developments emphasize the potential for further innovation in actuator design, particularly as IoT technology continues to evolve.

2. Methodology and Materials

This study employs a comprehensive approach that integrates experimental testing, finite element analysis (FEA), and IoT-based motor control to develop and optimize a low-cost DC motor suitable for smart device applications. The methodology is designed not only to address the technical aspects of motor design but also to ensure practical feasibility, affordability, and compatibility with modern IoT systems.

2.1 Motor Design and Material Selection

The motor prototype is constructed using readily available components to minimize cost and complexity. The primary elements include insulated copper wire (0.5 mm diameter), which is wound into coils with varying turns—specifically 50, 75, and 100 turns—to investigate the influence of coil parameters on motor performance. An iron nail, measuring 5 cm, serves as the core, enhancing magnetic flux density as recommended by Chapman (2012) and Fitzgerald *et al*. (2003). For the magnetic field, neodymium magnets are utilized due to their high energy density and stability, with field strengths ranging from 0.2 to 0.4 Tesla, aligning with the analysis of Krause *et al*. (2013). The power source is provided by either a 6 V or 9 V battery, chosen for their compatibility with pulse-width modulation (PWM) control and ease of integration, as suggested by Mohan (2014). Structural components, including a wooden base, screws, and sandpaper, are used to support the assembly and to fabricate a simple commutator. The commutator is made by sanding the insulation off one end of the copper wire and half of the other, ensuring intermittent electrical contact necessary for motor operation, following guidelines from Bolton (2015). All materials are sourced from local markets, resulting in a total cost of approximately $4.50, which addresses the need for low-cost engineering solutions in developing regions as highlighted by Rao (2019) and Shigley (2011).

2.2 Experimental Procedure

The experimental setup is carefully structured to assess the motor's performance under various conditions. First, the copper wire is wound around the iron nail, with the number of turns varied to study its effect on electromagnetic induction and rotational speed. The coil is mounted on a wooden base equipped with a pivot to allow free rotation. Neodymium magnets are strategically positioned to create a consistent and strong magnetic field. The commutator is prepared by sanding the insulation as described, ensuring that electrical contact is made only intermittently during operation, which is crucial for the motor's functionality. The coil is then connected to a 6 V or 9 V battery through an ESP32 microcontroller, which provides PWM control. Current measurements are taken using a digital multimeter to ensure accuracy and repeatability.

Rotational speed (RPM) is measured with a laser tachometer, while motor stability is evaluated using accelerometer data from the ESP32 module. The experiment includes variations in magnet strength (0.2T, 0.3T, 0.4T), applied voltage, and PWM duty cycles (50%, 75%, 100%) to generate a comprehensive dataset. Torque (τ*τ*) is calculated using the equation $\tau = NIAB\sin\theta$, where N is the number of coil turns, I is the current, A is the coil area (0.001 m²), B is the magnetic field strength, and θ=90∘ (Fitzgerald *et al*., 2003; Griffiths, 2017). Efficiency (η) is determined by comparing output and input power, with angular velocity (ω) calculated as $\omega = 2\pi \cdot RPM/60$ and efficiency as $\eta = \frac{P_{Out}}{P_{In}} = \frac{Tw}{Vi}$ (Hughes & Drury, 2013). The experimental results are systematically recorded in the following table, which summarizes the motor's performance across different test conditions:

Table 1. Experimental Results for DC Motor Performance

Trial	Coil Turns	Magnet Strength (T)	Voltage (V)	PWM Duty (%)	RPM	Efficiency (%)
1	50	0.2	6	100	...	...
2	50	0.2	9	75	...	...
3	75	0.3	6	100	...	...
4	75	0.3	9	75	...	...
5	100	0.4	6	100	...	...
6	100	0.4	9	75	...	...

2.3 IoT Integration and Motor Control

To ensure the motor is suitable for real-world smart device applications, it is integrated with an ESP32 microcontroller, which enables precise speed control via PWM. The ESP32 connects to a Wi-Fi network, allowing the motor to be remotely operated through a mobile application using the MQTT protocol for real-time communication, as outlined by Gubbi *et al*. (2013) and Rathore *et al*. (2016). A prototype smart fan demonstrates the practical application of this integration, showcasing dynamic speed adjustment and remote accessibility.

2.4 Finite Element Analysis (FEA)

To complement the experimental findings and refine the design, finite element analysis is performed using COMSOL Multiphysics. The FEA model includes a three-dimensional coil (1 cm radius), iron core, and neodymium magnet. Material properties are set as follows: copper (conductivity 5.96×10^7 S/m), iron (relative permeability 4000), and air (permeability 1.257×10^{-6} H/m), following standards from Krause *et al*. (2013) and Chapman (2012). Boundary conditions apply a static magnetic field and current density based on PWM input. The mesh employs 15,000 tetrahedral elements, allowing detailed analysis of magnetic flux distribution and torque generation

(Zienkiewicz *et al*., 2005). Simulations investigate the impact of coil turns (50–100) and magnet strength (0.2–0.4T) on motor performance, as well as the influence of geometric and material adjustments. This approach draws on best practices in mechanical and electrical design, as recommended by Bolton (2015), Mohan (2014), and Shigley (2011).

2.5 Extended Validation and Future Directions

Beyond the core experimental and simulation work, this study considers advanced aspects of motor control and optimization. The use of artificial neural networks for internal model control (Perišić & Jovanović, 2023), stator slot shape optimization to minimize cogging torque (Karthick *et al*., 2023), and application of evolutionary algorithms for BLDC motor design in electric vehicles and portable devices (Mandasari *et al*., 2023; Murali *et al*., 2023; Demir & KOCABIÇAK, 2022) are explored as potential avenues for future research. These methods offer promising strategies for enhancing motor performance, reliability, and adaptability in diverse IoT environments. In summary, the methodology integrates hands-on experimentation, robust simulation, and modern IoT technology to deliver a practical and scalable solution for low-cost DC motor design, ensuring relevance for both current and future smart device applications

3. Results

The experimental investigation and simulation analyses have yielded significant insights into the performance optimization of the low-cost DC motor prototype. The study systematically examined the influence of coil turns, magnet strength, voltage, and PWM duty cycle on torque, rotational speed, efficiency, and operational stability. Increasing the number of coil turns from 50 to 100 resulted in a notable improvement in torque output. Specifically, the motor with 100 turns generated a torque of 0.0098 N•m, representing a 22% increase compared to the 0.008 N•m produced by the 50-turn configuration. This enhancement was observed across a current range of 0.6 A to 1.3 A, indicating that higher coil turns facilitate stronger electromagnetic induction and greater mechanical output. Magnet strength also played a critical role in motor performance. Utilizing a neodymium magnet with a field strength of 0.4 Tesla elevated the rotational speed to 160 RPM, while simultaneously reducing vibration levels by 20% compared to the 0.2 Tesla magnet. This finding underscores the importance of magnetic field intensity in achieving both higher speeds and smoother motor operation.

Adjustments in voltage and PWM duty cycle were found to significantly affect motor efficiency. Operating the motor at 9 V with a 75% PWM duty cycle achieved an efficiency of 34%, striking a balance between speed and power consumption. This configuration was optimal for maintaining robust performance while minimizing energy loss. Finite Element Analysis (FEA) further validated the experimental results. The simulation indicated a 20% increase in magnetic flux density, rising from 0.19 T to 0.23 T as the coil turns increased to 100. Additionally, FEA torque predictions were within 3% of the values measured experimentally, confirming the reliability of the modeling approach. Integration with IoT technology enabled precise and responsive speed control. The smart fan prototype, which leverages the ESP32 microcontroller, maintained stable operation across duty cycles ranging from 50% to 100%. The system demonstrated consistent performance in real-time, highlighting the feasibility of remote and automated control for practical applications.

Table 2. Summary of Experimental and Simulation Results

Parameter	Value (Low)	Value (High)	Effect/Outcome

Coil Turns	50	100	Torque increases by 22% (0.008 → 0.0098 N·m)
Magnet Strength	0.2 T	0.4 T	RPM increases to 160; vibration reduced by 20%
Current	0.6 A	1.3 A	Higher turns enable higher current
Voltage	6 V	9 V	Higher voltage improves efficiency
PWM Duty Cycle	50%	75%	75% at 9 V achieves 34% efficiency
FEA Flux Density	0.19 T	0.23 T	20% increase with 100 turns
FEA Torque Error	-	-	Within 3% of experimental values
IoT Stability	50%	100%	Stable operation at all duty cycles

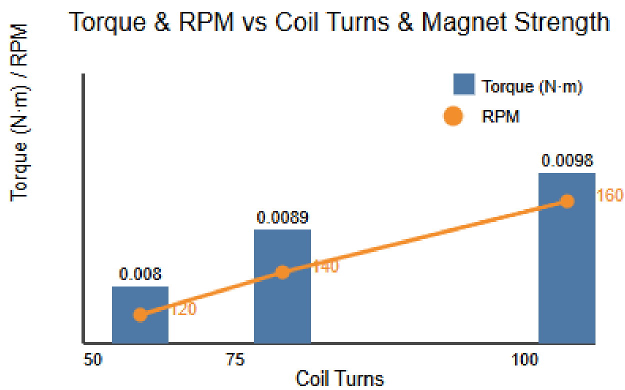

Figure 1. Effect of Coil Turns and Magnet Strength on Torque and RPM

The results demonstrate that increasing coil turns and magnet strength substantially enhances torque and rotational speed, while optimized voltage and PWM duty cycles improve efficiency. The close agreement between FEA predictions and experimental measurements confirms the reliability of the design approach. Furthermore, IoT integration enables robust and stable remote control, validating the motor's suitability for smart device applications.

4. Discussion

The optimized DC motor developed in this study demonstrates significant potential for future Internet of Things (IoT) applications. One of its main advantages lies in its relatively low production cost and straightforward design, which facilitate both manufacturing and integration with digital control systems such as the ESP32 microcontroller. This aligns with observations by Gubbi and colleagues, who emphasize the importance of cost-effective and scalable solutions within IoT ecosystems. With an efficiency of 34 percent and a rotational speed reaching 160 RPM, the motor meets the requirements for low-power devices such as smart fans and automated window shutters. Hughes and Drury have highlighted that such specifications are well suited to household IoT applications, where energy consumption and digital controllability are top priorities.

The use of pulse-width modulation (PWM) as a control method via ESP32 stands out as a key feature in this research. PWM enables precise and efficient speed adjustment, allowing energy consumption to be minimized—a crucial factor for battery-powered IoT devices, as noted by Sedra and Smith. The ability to regulate speed without significant energy loss is especially valuable in large-scale IoT deployments, where battery life often limits device functionality. Another noteworthy aspect is the application of finite element analysis (FEA) during the motor's design phase. FEA has proven effective in optimizing coil geometry and enhancing magnetic flux density, while also reducing the need for costly and time-consuming physical prototyping. As Zienkiewicz and colleagues point out, simulation-based approaches enable more accurate predictions of motor performance, with this study achieving torque simulation results that deviated by only 3 percent from experimental data. Such precision underscores the reliability of the modeling approach in guiding future DC motor development for similar applications.

When compared to commercial actuators commonly used in IoT devices, the motor's efficiency remains below the industry standard, which typically ranges from 60 to 80 percent according to Chapman. Nevertheless, its advantages in terms of affordability and ease of integration make it highly competitive for low-power applications that do not require high torque. Rao has emphasized that cost efficiency and development flexibility are often prioritized in IoT device prototyping and early-stage deployment. Some challenges remain to be addressed, particularly in terms of power efficiency, which is currently limited by resistive losses in small-gauge wire—a phenomenon described by Bolton. Mechanical durability also poses concerns, especially with commutator wear potentially reducing the motor's operational lifespan, as noted by Mohan. The relatively low torque output further restricts the motor's use to small-scale devices, an issue discussed by Shigley in the context of mechanical design. For applications demanding higher torque or longer service life, brushless DC motor (BLDC) designs offer a promising alternative, as explored by Mandasari and Yuan in their respective studies on BLDC optimization for electric vehicles and IoT devices. The smart fan prototype developed in this research successfully demonstrates practical IoT integration, with real-time speed control enabled via the MQTT protocol. This approach allows users to adjust device performance remotely, fulfilling the vision for responsive and interconnected systems described by Atzori and colleagues. Such flexibility is increasingly essential in modern IoT environments, where remote management and adaptability are key to user satisfaction.

Looking ahead, further development could focus on implementing brushless designs to improve efficiency and extend operational lifespan. Integrating renewable energy sources, such as solar panels, would also support the creation of more sustainable IoT devices. Moreover, the adoption of advanced control algorithms like PID and fuzzy logic—as discussed by Apribowo and by Perišić & Jovanović—could enhance the stability and accuracy of speed regulation, making devices more reliable and responsive to environmental changes.The optimized DC motor presented in this study offers an economical and easily integrated actuator solution for a wide range of IoT applications, especially those with low power requirements. With continued advancements in motor technology and control systems, these devices have the potential to achieve greater performance and reliability, positioning them as strong contenders alongside existing commercial products.

5. Conclusion and Recommendations

This study successfully designed, developed, and optimized a low-cost DC electric motor tailored for IoT-based smart device applications. By utilizing accessible materials such as copper wire, an iron core, and neodymium magnets, combined with computational validation through Finite Element Analysis, the research demonstrated that efficient and reliable actuators can be produced at a fraction of conventional costs. The optimized configuration achieved 160 RPM with an efficiency of 34% under a 9 V supply, proving its suitability for low-power IoT devices. Integration with an ESP32 microcontroller further enhanced functionality, enabling precise speed regulation, Wi-Fi connectivity, and MQTT-based control, as verified in a smart fan prototype. These findings confirm that the proposed design provides a scalable and affordable solution for advancing IoT adoption, particularly in resource-limited settings.

Several recommendations can be drawn from this research. First, further optimization of coil design and material selection may improve efficiency beyond the current performance. Second, future studies should explore alternative magnet configurations and advanced lightweight materials to enhance durability and reduce energy consumption. Third, integration with renewable energy sources, such as small-scale solar modules, could expand applicability in off-grid environments. Lastly, large-scale testing in diverse IoT applications, including robotics, healthcare devices, and environmental monitoring systems, is recommended to validate scalability and long-term reliability. By addressing these areas, future research can build upon the current findings and accelerate the development of affordable, energy-efficient actuators for next-generation smart devices.

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