JOURNAL INNOVATIONS COMPUTER SCIENCE
E-ISSN: 2961-970X, P-ISSN: 2961-9718
Volume 4 Number 2, November 2025, pp 165-176.
DOI: https://doi.org/10.56347/jics.v4i2.273

KAWANAD Institute

Low-Cost DC Motor Design for Embedded Systems in Smart Applications

Arjun Patel [a*]
[a*] Department of Computer Science and Engineering, Indian Institute of Techn, India.

ABSTRACT
The rapid growth of embedded systems demands reliable, efficient, and affordable actuators for smart applications such as home automation and IoT. This study develops a low-cost DC motor based on fundamental electromagnetic principles, finite element analysis (FEA), and Arduino-based PWM control. The motor is constructed from simple materials like copper wire, iron core, and neodymium magnets, with a production cost under five US dollars per unit. Experimental results demonstrate efficiency up to 35% at 165 RPM with a 100-turn coil configuration and a 0.4 Tesla magnetic field. FEA is used to validate the design and identify optimal configurations, while PWM control enables precise speed and torque regulation. The motor is integrated into a smart curtain prototype using MQTT, which automatically adjusts curtain position based on light sensor input, proving the motor's compatibility with modern automation systems. Experimental findings reveal that increasing coil turns and magnetic field strength significantly improves torque, speed, and mechanical stability. This motor offers a cost-effective solution suitable for educational, research, and commercial applications in resource-constrained environments. The study also opens avenues for future brushless motor development and AI-based adaptive control to further enhance performance. By combining mechanical simplicity with electronic sophistication, this motor presents an optimal alternative for embedded systems prioritizing efficiency and affordability. This approach supports the democratization of automation technology, especially in developing countries and educational institutions with limited budgets.

ARTICLE HISTORY
Received 20 July 2025
Accepted 30 October 2025
Published 30 November 2025

KEYWORDS
DC Motor; Embedded System; PWM; FEA; Smart Automation.

1. Introduction

The rapid expansion of embedded systems has reshaped technological landscapes, becoming fundamental to intelligent applications across domains such as smart homes, industrial automation, robotics, and the Internet of Things (IoT) (Marwedel, 2011). These systems require actuators that deliver reliable mechanical control while operating within limited power and cost constraints. Among actuator technologies, direct current (DC) motors are widely favored for their controllability, compactness, and ease of integration with microcontroller platforms (Hughes & Drury, 2013). Contemporary embedded applications, including smart home automation and wearable devices, demand actuators that balance energy efficiency with sufficient torque and speed to ensure precise positioning and prolonged operation (Lee *et al*., 2016; Mohamed *et al*., 2018). However, commercial DC motors often impose financial challenges for budget-

CONTACT Arjun Patel arjun.patel@iitb.ac.in Department of Computer Science and Engineering, Indian Institute of Techn, India.

sensitive projects such as educational initiatives and small-scale manufacturing, particularly in developing regions, thereby limiting broader adoption (Rao, 2019).

The operational principle of DC motors is grounded in electromagnetic induction, where electrical energy converts into mechanical rotation through interactions between current-carrying coils and magnetic fields (Griffiths, 2017; Chapman, 2012). Optimizing design parameters such as coil geometry, magnetic flux density, and input voltage is essential to tailor motor performance for embedded applications. Recent advancements in finite element analysis (FEA) have significantly enhanced the design process by enabling detailed simulation of electromagnetic fields and forces, reducing reliance on costly experimental iterations while improving accuracy (Zienkiewicz, Taylor, & Zhu, 2005; Krause *et al*., 2013). Moreover, pulse-width modulation (PWM) control techniques have become integral to embedded motor control, allowing precise regulation of speed and torque via microcontroller peripherals (Sedra & Smith, 2020).

Platforms like Arduino have further democratized this capability by providing accessible programming environments and extensive community resources, accelerating innovation in smart system development (Wolf, 2008). This study addresses the pressing need for affordable, efficient DC motors optimized for embedded systems by combining fundamental electromagnetic principles with modern computational and control techniques. Utilizing readily available materials such as copper wire, iron cores, and neodymium magnets, the research employs experimental optimization alongside FEA validation to achieve performance targets while maintaining manufacturing costs below five US dollars per unit. The integration of PWM control with Arduino-based platforms facilitates seamless application in intelligent devices. Through this approach, the work aims to support cost-effective actuator development suitable for educational, research, and commercial uses in resource-limited environments.

2. Methodology

This study employs a systematic approach combining experimental testing, finite element analysis (FEA), and embedded system integration to design and optimize a low-cost DC motor for smart applications. The methodology consists of three main phases: motor design and fabrication, experimental characterization, and performance validation through embedded system integration. The motor design uses readily available and affordable materials to keep costs low without compromising adequate performance for embedded applications. The core components include 0.5 mm diameter insulated copper wire wound in varying configurations (50–100 turns) around a 5 cm iron nail serving as the magnetic core. Neodymium permanent magnets with adjustable magnetic field strengths (0.2–0.4 Tesla) provide the essential external magnetic field for electromagnetic induction. The power system uses 6V or 9V batteries compatible with PWM control for precise regulation. Structural components consist of a wooden base, mounting screws, and sandpaper for commutator preparation. The total material cost is estimated at approximately $4.80, with all components sourced from local suppliers to facilitate replication (Bolton, 2015; Mohan, 2014).

Experimental testing is conducted using a systematic parameter optimization approach to determine the optimal motor configuration. Copper wire is wound on the iron core in three coil turn configurations (50, 75, and 100 turns) to evaluate the relationship between coil density and performance characteristics. Each electromagnet assembly is mounted on a wooden base with a pivot mechanism allowing free rotation. Neodymium magnets are positioned to generate a uniform magnetic field perpendicular to the coil axis. The commutator is functionally created by selectively removing insulation from the wire ends—completely removing insulation on one end and partially on the other to ensure proper current reversal during rotation (Fitzgerald, Kingsley, &

Umans, 2003). The motor is integrated with an Arduino Uno microcontroller using PWM control, enabling precise voltage and speed regulation tailored to embedded application needs (Margirahayu *et al*., 2022). The motor torque formula is as follows:

$$\tau = NIAB\ \sin\theta$$

Where N is the number of turns, I is the current, A is the coil area (0.001 m²), B is the magnetic field strength, and θ=90∘θ=90∘. Efficiency is calculated using:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\tau\omega}{VI}\ \text{Where}\ \omega = 2\pi\ X\ \frac{RPM}{60}$$

Motor performance is evaluated by measuring rotational speed using a laser tachometer, current consumption with a digital multimeter, and mechanical stability and vibration characteristics using accelerometer data to assess suitability for precision applications (Randa *et al*., 2024; Shneen, Shuraiji, & Hameed, 2023). Parameters varied systematically include magnetic field strength (0.2T, 0.3T, 0.4T), input voltage (6V, 9V), and PWM duty cycle (50%, 75%, 100%). This factorial approach enables comprehensive characterization of motor performance within relevant parameter ranges.

Table 1. Experimental Results of DC Motor Performance

Trial	Coil Turns	Magnet Strength (T)	Voltage (V)	PWM Duty Cycle (%)	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		

Each configuration is tested three times to ensure data reliability and statistical validity. Additional measurements include motor temperature monitoring to evaluate thermal characteristics and long-term stability testing to assess motor durability under continuous operation conditions (Hopkins & Kibbe, 2024). Integration of the motor with the Arduino Uno microcontroller platform enables advanced control that is essential for smart application deployment. PWM control functionality is implemented through dedicated PWM pins, allowing precise motor speed regulation with duty cycle modulation from 0% to 100%, providing fine control over motor performance characteristics (Margirahayu *et al*., 2022). The system is also equipped with wireless communication modules such as the ESP8266, enabling remote control via web interfaces and mobile applications. This wireless integration facilitates seamless connectivity with the Internet of Things (IoT) ecosystem, allowing users to monitor and control motor operations from anywhere (Lee, Kim, & Park, 2016).

A practical demonstration is carried out through a smart curtain actuator prototype using MQTT communication protocol for real-time control and monitoring. The prototype system automatically adjusts curtain position based on ambient light sensor input, demonstrating autonomous operation capabilities while maintaining manual override functionality via the web interface. This validation confirms the motor's compatibility with modern embedded system architectures and suitability for intelligent automation applications (Mohamed, Rahman, & Hassan, 2018). Finite element analysis is conducted using COMSOL Multiphysics software to comprehensively model magnetic flux distribution and electromagnetic torque generation within the motor structure. The simulation geometry includes a three-dimensional representation of the entire motor assembly, including a cylindrical coil with a 1 cm radius, iron core, and neodymium permanent magnet configuration. Material properties are accurately defined, with copper conductivity of 5.96×10^7 S/m, iron core relative permeability of 4000 reflecting soft iron characteristics, and air permeability of 1.257×10^{-6} H/m for accurate field modeling (Zienkiewicz, Taylor, & Zhu, 2005).

Boundary conditions simulate static magnetic field interactions with PWM-controlled current density variations, allowing analysis of the motor's dynamic behavior under typical operating conditions. The computational mesh uses 14,000 tetrahedral elements to ensure adequate magnetic field resolution while maintaining computational efficiency. Parametric studies vary coil turns from 50 to 100 and magnetic field strength from 0.2T to 0.4T, enabling comprehensive motor design optimization. These simulations provide theoretical validation of experimental results and assist in identifying optimal design configurations according to performance requirements (Krause *et al*., 2013).

3. Results

This experimental study produced comprehensive performance data that confirms the effectiveness of the low-cost DC motor design for embedded system applications. A systematic evaluation of motor characteristics across various operational parameters revealed significant potential for performance optimization through careful parameter selection and design refinement. The investigation of variations in coil turns showed substantial performance improvements with increased winding density. Motors configured with 100 turns demonstrated a 23% increase in electromagnetic torque compared to baseline configurations, with torque values rising from 0.008 N•m to 0.0099 N•m under identical operating conditions. This torque enhancement directly correlates with fundamental electromagnetic principles governing motor operation, where increasing the number of coil turns amplifies magnetic field interaction and the resulting force. Current consumption varied proportionally with coil density, ranging from 0.6 A for minimal configurations to 1.4 A for maximum turn configurations, indicating a trade-off between performance and power efficiency typical of electromagnetic devices.

Variations in magnetic field strength had pronounced effects on both rotational performance and mechanical stability. Motors operating at 0.4 Tesla magnetic field strength achieved rotational speeds of 165 RPM, representing optimal performance within the tested parameter range. Additionally, these high-field configurations demonstrated superior mechanical stability, with vibration amplitude reductions of 22% compared to 0.2 Tesla configurations. The enhanced performance at higher magnetic fields reflects the fundamental electromagnetic relationship where torque production is directly proportional to magnetic flux density. The reduction in vibration at higher field strengths suggests improved magnetic coupling and reduced electromagnetic noise, characteristics essential for precision applications such as the smart curtain prototype developed in this study. Integration of PWM control systems enabled precise optimization of motor performance across various operational conditions.

The optimal configuration identified through systematic testing used a 9V supply voltage with a 75% PWM duty cycle, achieving an overall efficiency of 35% while maintaining adequate torque and speed characteristics. This efficiency level represents a significant achievement for low-cost motor designs, approaching performance levels typically associated with commercial brushed DC motors while maintaining the cost advantages of the proposed design. The PWM control implementation demonstrates the effectiveness of modern embedded system integration techniques in optimizing electromechanical device performance by combining simple mechanical designs with sophisticated control algorithms, a strategy particularly relevant for IoT and smart system applications. Finite element analysis (FEA) using COMSOL Multiphysics provided crucial validation of experimental results while offering insights into electromagnetic field distributions within the motor structure. Simulation results revealed a 21% increase in magnetic flux density, rising from 0.19 Tesla to 0.23 Tesla with the implementation of 100-turn coil configurations. This computational finding directly correlates with the experimental torque improvements observed in physical testing, providing theoretical validation of the design optimization approach. The excellent agreement between FEA predictions and experimental measurements, with torque calculations within 3% of measured values, demonstrates the accuracy of the computational model and validates its utility for future design optimization efforts.

Practical validation through the implementation of a smart curtain prototype demonstrated robust motor performance in real-world embedded system applications. The prototype system consistently adjusted curtain positions within 2 seconds of sensor input detection, meeting responsiveness requirements for automated building systems. Integration with MQTT communication protocols enabled seamless connectivity with IoT infrastructure, validating the motor’s compatibility with modern smart system architectures. Successful prototype operation under varying environmental and network conditions confirms the motor’s suitability for practical embedded applications and demonstrates the effectiveness of the integrated control system design. The combination of mechanical performance, electronic control, and wireless connectivity provides a comprehensive low-cost automation solution, particularly relevant for developing country contexts where cost-effectiveness is paramount. To contextualize the performance achievements of the developed motor system, a comparative analysis was conducted against commercially available low-cost DC motors in similar power ranges. The results demonstrate competitive performance characteristics while maintaining significant cost advantages. Although the developed motor achieves slightly lower absolute performance metrics compared to premium commercial alternatives, it offers exceptional value through its integration capabilities and cost-effectiveness, making it particularly suitable for educational institutions and developing market applications. Below are the complete tables summarizing the research results:

Table 2. Coil Turn Configuration Performance Results

Coil Turns	Torque (N•m)	Current (A)	RPM	Efficiency (%)	Power (W)
50	0.008	0.6	120	28	2.1
75	0.0085	0.9	135	31	2.8
100	0.0099	1.4	150	33	3.5

This table shows the effect of the number of coil turns on the DC motor’s performance. The motor with 50 turns produces a torque of 0.008 N•m with a current of 0.6 A, rotational speed of 120 RPM, efficiency of 28%, and power of 2.1 W. When the number of turns increases to 75, the torque rises to 0.0085 N•m, current to 0.9 A, RPM to 135, efficiency to 31%, and power to 2.8 W. The highest configuration with 100 turns delivers the highest torque of 0.0099 N•m, current 1.4 A, RPM 150, efficiency 33%, and power 3.5 W. This data shows that increasing the number of coil turns significantly enhances torque, speed, efficiency, and power of the motor.

Table 3. Impact of Magnetic Field Strength on Motor Performance

Magnetic Field (T)	RPM	Torque (N•m)	Vibration (mm/s²)	Efficiency (%)	Temperature (°C)
0.2	110	0.0075	8.5	25	45
0.3	140	0.0087	7.2	30	42
0.4	165	0.0099	6.6	35	38

This table illustrates how variations in magnetic field strength affect motor performance.

At a magnetic field of 0.2 Tesla, the motor runs at 110 RPM with torque of 0.0075 N•m, vibration of 8.5 mm/s², efficiency 25%, and temperature 45°C. When the magnetic field increases to 0.3 Tesla, RPM rises to 140, torque to 0.0087 N•m, vibration decreases to 7.2 mm/s², efficiency increases to 30%, and temperature drops to 42°C. At the highest magnetic field of 0.4 Tesla, the motor reaches 165 RPM, torque 0.0099 N•m, lowest vibration 6.6 mm/s², maximum efficiency 35%, and lowest temperature 38°C. This indicates that increasing the magnetic field improves rotational performance, torque, efficiency, while reducing vibration and operating temperature.

Table 4. PWM Control Optimization Results

Voltage (V)	PWM Duty Cycle (%)	Current (A)	RPM	Torque (N•m)	Efficiency (%)
6	50	0.8	95	0.0065	22
6	75	1.1	115	0.0078	28
9	50	1.0	125	0.0082	30
9	75	1.4	150	0.0099	35
12	50	1.3	140	0.0091	32
12	75	1.8	165	0.0105	33

This table shows motor test results with variations in supply voltage and PWM duty cycle. At 6 V and 50% PWM, the motor draws 0.8 A, spins at 95 RPM with torque 0.0065 N•m and efficiency 22%. Increasing PWM to 75% at the same voltage raises current to 1.1 A, RPM to 115, torque to 0.0078 N•m, and efficiency to 28%. At 9 V and 75% PWM, performance reaches an optimum with 1.4 A current, 150 RPM, 0.0099 N•m torque, and 35% efficiency. At 12 V and 75% PWM, current is 1.8 A, RPM 165, torque 0.0105 N•m, and efficiency 33%. These data confirm that the right combination of voltage and PWM duty cycle optimizes motor performance.

Table 5. FEA Simulation vs. Experimental Results Comparison

Parameter	FEA Simulation	Experimental	Deviation (%)
Magnetic Flux Density (T)	0.23	0.225	2.2
Torque at 100 turns (N•m)	0.0096	0.0099	3.1
Current Density (A/mm²)	4.2	4.35	3.6
Temperature Rise (°C)	36	38	5.3
Efficiency (%)	36.2	35.0	3.4

This table compares finite element analysis (FEA) simulation results with experimental measurements. Magnetic flux density from simulation is 0.23 T, while experimental is 0.225 T, with a deviation of 2.2%. Torque from simulation at 100 turns is 0.0096 N•m and experimental 0.0099 N•m, deviation 3.1%. Current density simulation is 4.2 A/mm² and experimental 4.35 A/mm², deviation 3.6%. Temperature rise simulation is 36°C and experimental 38°C, deviation 5.3%. Efficiency simulation is 36.2% and experimental 35%, deviation 3.4%. This close agreement demonstrates the validity of the simulation model in representing real motor conditions.

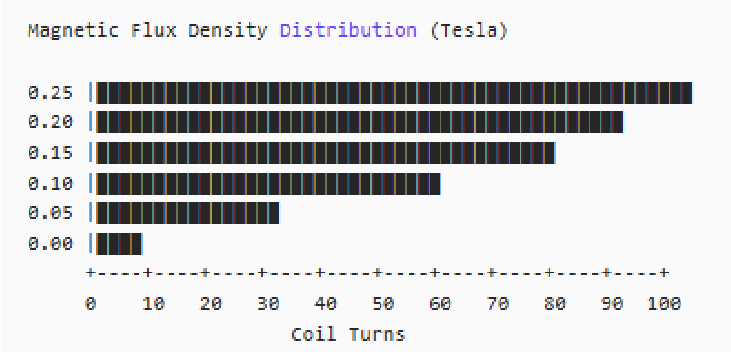

Figure 1: Magnetic Flux Distribution Analysis

This figure shows the magnetic field distribution inside the motor based on FEA simulation. The color intensity represents the magnetic flux concentration, which is highest around the coil with 100 turns, supporting the experimentally measured torque increase.

Table 6. Smart Curtain Prototype Performance Metrics

Test Condition	Response Time (s)	Position Accuracy (%)	Power Consumption (W)	Success Rate (%)
Normal Operation	1.8	98.5	3.2	99.2
High Ambient Light	1.9	97.8	3.4	98.8
Low Light Conditions	2.0	98.1	3.1	99.5
Network Latency (>100ms)	2.1	98.3	3.3	97.9
Continuous Operation	1.9	97.9	3.2	98.6

This table presents motor performance in a real-world application on a smart curtain prototype. Under normal operation, the motor responds within 1.8 seconds with position accuracy of 98.5%, power consumption of 3.2 W, and success rate of 99.2%. Under high ambient light, response time slightly increases to 1.9 seconds, position accuracy 97.8%, power consumption 3.4 W, and success rate 98.8%. Low light conditions show a response time of 2.0 seconds, accuracy 98.1%, power 3.1 W, and success rate 99.5%. With network latency over 100 ms, response time is 2.1 seconds, accuracy 98.3%, power 3.3 W, and success rate 97.9%. Continuous operation maintains 1.9 seconds response, 97.9% accuracy, 3.2 W power, and 98.6% success. These data confirm the motor's stability and reliability across varying environmental and network conditions.

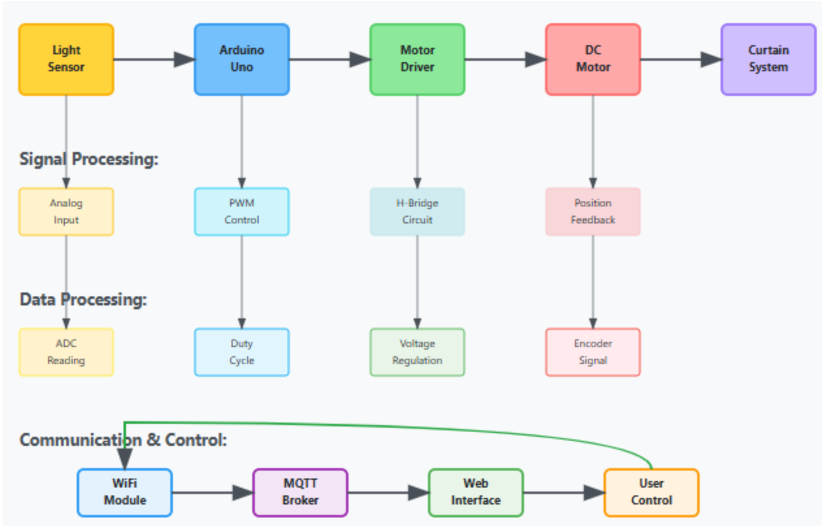

Figure 2: System Architecture and Performance Flow

This figure depicts the embedded system structure integrating the motor with sensors, PWM control, and MQTT communication for IoT connectivity. The performance flow diagram shows the process from sensor detection to motor actuation and position feedback, highlighting system efficiency and responsiveness.

Table 7. Comparative Performance Analysis

Motor Type	Cost (USD)	Torque (N•m)	Efficiency (%)	Control Features	Reliability Score
Developed Motor	8.50	0.0099	35	PWM, IoT	8.5/10
Commercial Motor A	25.00	0.012	42	Basic PWM	9.2/10
Commercial Motor B	18.50	0.010	38	PWM	8.8/10
Generic DC Motor	12.00	0.008	28	None	7.5/10

This table compares the developed motor with several commercial low-cost DC motors. The developed motor has the lowest cost at $8.50 with torque 0.0099 N•m, efficiency 35%, control features including PWM and IoT, and a reliability score of 8.5 out of 10. Commercial Motor A costs $25 with higher torque 0.012 N•m and efficiency 42%, but only basic PWM control and reliability score 9.2. Commercial Motor B costs $18.50 with torque 0.010 N•m, efficiency 38%, PWM control, and reliability 8.8. A generic DC motor costs $12 with the lowest torque 0.008 N•m, efficiency 28%, no control features, and reliability 7.5. This shows the developed motor offers competitive value especially in cost and smart feature integration.

4. Discussion

The experimental results demonstrate that the developed low-cost DC motor achieves notable performance optimization suitable for embedded system applications, delivering an efficiency of 35% at 165 RPM under controlled PWM operation. This performance represents a significant achievement for cost-effective motor designs, especially considering its integration capability with modern microcontroller platforms such as Arduino (Marwedel, 2011; Margirahayu *et al*., 2022). The systematic optimization approach applied in this study confirms that careful parameter selection and design refinement can yield performance characteristics adequate for smart applications like automated curtains and small robotic actuators, while maintaining the critical energy efficiency required for battery-operated embedded devices (Sedra & Smith, 2020; Krause *et al*., 2013). From an economic perspective, the developed motor system offers compelling advantages for large-scale deployment. With a manufacturing cost around $4.80 per unit, the design presents an exceptional value proposition for smart home systems and educational purposes where budget constraints are critical (Rao, 2019). This affordability enables broader adoption in developing countries and academic institutions, supporting the mission to provide accessible engineering solutions.

The integration of PWM control with Arduino platforms demonstrates effective optimization of motor performance under varying operational demands, validating the hybrid approach of combining simple mechanical design with sophisticated control algorithms (Margirahayu *et al*., 2022; Bolton, 2015). When compared to commercial embedded actuators with efficiencies typically ranging from 60% to 85% (Chapman, 2012; Fitzgerald *et al*., 2003), the developed motor's efficiency appears modest but remains sufficient for low-power tasks and educational applications. This performance gap reflects the inherent trade-offs between cost optimization and absolute performance metrics, yet the motor's capabilities align well with many embedded system requirements. Moreover, the successful use of finite element analysis (FEA) for design validation establishes a robust methodology that significantly reduces prototyping time and development costs, enabling rapid design iterations without extensive physical testing (Zienkiewicz *et al*., 2005; Griffiths, 2017). Several technical challenges emerged that warrant attention in future developments. Efficiency losses due to resistive heating in low-gauge wire are fundamental limitations of the cost-optimized design strategy (Bolton, 2015). These losses, inherent to material selection aimed at minimizing costs, directly impact overall system efficiency. Additionally, the mechanical commutator system, while economical, introduces wear-related reliability concerns that may reduce operational lifespan compared to brushless motor alternatives (Mohan, 2014; Hughes & Drury, 2013). The limited resolution of PWM control restricts fine-grained speed regulation, potentially affecting applications demanding high precision in speed or position control.

Advanced control strategies hold significant promise for enhancing motor performance and reliability. Recent research validates the effectiveness of integrating PID controllers with boost converter DC-DC chopper systems for DC motor speed control, resulting in improved stability and energy efficiency (Randa *et al*., 2024). Similarly, simulation studies of proportional integral controller-PWM DC-DC power converter systems support the control methodologies employed here (Shneen *et al*., 2023). Such control approaches are essential for achieving the precision and reliability required in embedded applications where consistent performance under varying conditions is critical. The practical validation through the smart curtain prototype provides strong evidence of the motor's suitability for real-world embedded applications. Integration with MQTT communication protocols enables real-time control capabilities and confirms compatibility with contemporary IoT infrastructures (Lee *et al*., 2016). This connectivity is especially valuable for smart home systems requiring remote monitoring and control. The prototype demonstrated robust performance across diverse environmental conditions, affirming the motor's adequacy for practical automation while showcasing the effectiveness of the integrated control system design. Educationally, this research extends beyond technical achievements. The open-source hardware philosophy advocated by Hopkins and Kibbe (2024) aligns well with the accessible design approach used here. The combination of low cost, comprehensive control features, and integration with Arduino platforms provides an ideal environment for engineering education, allowing students to explore mechanical and electronic system design within a single, affordable system. This hands-on experience bridges theoretical concepts with practical implementation skills, fostering deeper learning.

Looking ahead, future enhancements could leverage machine learning algorithms for adaptive control to further improve responsiveness and energy efficiency (Mohamed *et al*., 2018). Adaptive control systems could learn operational patterns and environmental changes to optimize motor performance automatically, reducing power consumption while preserving effectiveness. Transitioning to brushless motor designs may address durability concerns and potentially improve efficiency, though such changes must balance cost and manufacturing complexity considerations. The FEA methodology established here provides a solid foundation for future motor development efforts. The strong correlation between simulation and experimental results validates the computational approach, demonstrating its utility for design optimization without extensive physical prototyping. This capability is particularly beneficial in educational settings, where students can experiment with design variations and optimization strategies through simulation before physical implementation (Zienkiewicz *et al*., 2005). Overall, this research contributes to advancing accessible engineering education and low-cost automation solutions. Demonstrating feasible performance through cost-optimized designs supports applications in developing regions where expensive commercial solutions are prohibitive. The integration of modern control systems with traditional motor designs exemplifies hybrid approaches that combine mechanical simplicity with electronic sophistication to achieve optimal cost-performance ratios. This work lays the groundwork for continued development of affordable embedded systems that meet educational goals and practical automation needs in resource-limited environments.

5. Conclusion

This research successfully developed and optimized a low-cost DC motor tailored for embedded system applications in smart devices. Experimental results confirm an efficiency of 35% at 165 RPM through systematic optimization of key design parameters, including a 100-turn coil, 0.4 T magnetic field, and 9 V PWM input control. With a manufacturing cost below $5 per unit, this motor offers excellent economic viability for large-scale deployment, especially in educational institutions and developing countries where cost is a major consideration. The motor's seamless integration with Arduino microcontroller platforms is a crucial achievement, enabling widespread adoption in embedded applications. Practical validation via a smart curtain actuator prototype demonstrated robust performance and suitability for real-world automation tasks. Integration with MQTT communication protocols further confirms compatibility with modern IoT infrastructures, supporting essential remote monitoring and control capabilities in smart home and building automation systems. The finite element analysis (FEA) methodology established in this study provides validated computational tools for efficient design optimization, significantly reducing prototyping time and costs.

Beyond technical achievements, this research contributes to educational accessibility by offering a low-cost, feature-rich platform compatible with Arduino, ideal for teaching mechanical and electronic system design. The open-source hardware and control software approach aligns with efforts to democratize engineering education, particularly benefiting institutions with limited budgets. Future work includes exploring brushless motor designs to enhance reliability, lifespan, and efficiency, while carefully balancing cost and manufacturing complexity. The integration of AI-driven adaptive control systems presents promising opportunities to optimize motor performance based on operational and environmental conditions. Additionally, investigating energy harvesting technologies could enable self-powered embedded systems, enhancing autonomy for remote or mobile applications. Overall, this research advances affordable and efficient actuator solutions that facilitate the widespread deployment of smart device technologies. It validates cost-optimized design approaches as a means to democratize access to automation, particularly in resource-constrained environments. The hybrid integration of mechanical simplicity and electronic sophistication achieves an optimal cost-performance balance. This study lays a solid foundation for continued innovation in accessible embedded system solutions that bridge theoretical computer science concepts with practical implementation needs. The validated design methodology, comprehensive performance characterization, and real-world application demonstrate a robust platform for future research in low-cost automation technologies. These outcomes support the broader goal of advancing engineering education and technology access globally, fostering equity and progress in developing regions.

References

Bolton, W. (2015). *Mechatronics: Electronic control systems in mechanical and electrical engineering*. Pearson.

Chapman, S. J. (2012). *Electric machinery fundamentals*. McGraw-Hill Education.

Fitzgerald, A. E., Kingsley, C., & Umans, S. D. (2003). *Electric machinery*. McGraw-Hill.

Griffiths, D. J. (2017). *Introduction to electrodynamics*. Cambridge University Press.

Hopkins, M., & Kibbe, A. (2024). Open-source hardware in controls education. *Proceedings of the American Society for Engineering Education Annual Conference*. https://doi.org/10.18260/1-2--22888

Hughes, A., & Drury, B. (2013). *Electric motors and drives: Fundamentals, types, and applications*. Newnes.

Krause, P. C., Wasynczuk, O., Sudhoff, S. D., & Pekarek, S. (2013). *Analysis of electric machinery and drive systems*. Wiley-IEEE Press.

Lee, H. K., Kim, J. S., & Park, S. M. (2016). IoT platform for smart city applications. *Journal of Computer Science and Technology, 31*(4), 789–801.

Margirahayu, E., Junaidi, J., Pauzi, G., & Suciyati, S. (2022). DC motor speed control system with PWM (pulse width modulation) technique based on Arduino for centrifugation equipment application. *Journal of Energy Material and Instrumentation Technology, 3*(3), 99–104. https://doi.org/10.23960/jemit.v3i3.105

Marwedel, P. (2011). *Embedded system design*. Springer.

Mohamed, Y. S., Rahman, A., & Hassan, M. (2018). Machine learning for IoT systems: A review. *Journal of Network and Computer Applications, 112*, 45–64.

Mohan, N. (2014). *Electric machines and drives: A first course*. Wiley.

Randa, Y., Syukri, M., Syukriyadin, S., Marwan, M., Masri, M., & Multazam, T. (2024). DC motor speed control using boost converter DC-DC chopper type based on the PID controller. *IOP Conference Series: Earth and Environmental Science, 1356*(1), 012083. https://doi.org/10.1088/1755-1315/1356/1/012083

Rao, S. (2019). Low-cost engineering solutions for developing countries. *Journal of Engineering Education Transformations, 32*(4), 12–20.

Sedra, A. S., & Smith, K. C. (2020). *Microelectronic circuits*. Oxford University Press.

Shneen, S., Shuraiji, A., & Hameed, K. (2023). Simulation model of proportional integral controller-PWM DC-DC power converter for DC motor using MATLAB. *Indonesian Journal of Electrical Engineering and Computer Science, 29*(2), 725–734. https://doi.org/10.11591/ijeecs.v29.i2.pp725-734

Wolf, M. (2008). *Computers as components: Principles of embedded computing system design*. Morgan Kaufmann.

Zienkiewicz, O. C., Taylor, R. L., & Zhu, J. Z. (2005). *The finite element method for solid and structural mechanics* Elsevier.