

Development and Performance Evaluation of an Arduino-Based Temperature-Controlled Variable-Speed Fan System

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KEYWORDS

Arduino Uno, DC Motor Drive, Pulse Width Modulation (PWM), Temperature-Based Speed Control, Variable-Speed Fan

ABSTRACT

This study presents the development and experimental evaluation of an Arduino-based temperature-controlled variable-speed fan system for adaptive cooling applications. The proposed system employs an Arduino Uno as the main controller, a DHT11 sensor for ambient temperature measurement, and Pulse Width Modulation (PWM) to regulate the speed of a DC fan motor through a motor driver circuit. The control strategy automatically adjusts the PWM duty cycle according to predefined temperature ranges, thereby varying the fan speed according to cooling demand. Experimental evaluation was conducted at different PWM operating conditions by measuring motor voltage, current, and rotational speed. The influence of mechanical loading was further investigated using laminated and hard paper fan blades with different load characteristics. The results demonstrate that increasing the PWM duty cycle increases the average motor voltage and rotational speed, with a maximum measured speed of approximately 14,041 rpm. Under heavier blade loading, higher motor current and lower rotational speed were observed, which are consistent with the torque-current and speed-load characteristics of a DC motor. Overall, the developed system demonstrates the feasibility of low-cost automatic temperature-based fan speed regulation while providing a practical platform for evaluating PWM-controlled DC motor drive performance.

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1. INTRODUCTION

Electric drive systems are widely employed in modern engineering applications due to their capability to provide efficient and controllable conversion of electrical energy into mechanical motion. Their applications extend across industrial automation, transportation, household appliances, and heating, ventilation, and air-conditioning (HVAC) systems. Among these applications, electric fans represent one of the most common motor-driven cooling devices used in residential, commercial, and industrial environments. Conventional fan systems typically operate at fixed or manually selected speed levels, which may result in unnecessary power consumption when maximum cooling is not required. Therefore, incorporating automatic variable-speed operation according to environmental conditions offers a practical approach for improving the utilization of electrical energy while maintaining the required cooling performance [1], [2].

Pulse Width Modulation (PWM) is widely employed for DC motor speed regulation because it controls the average voltage applied to the motor by varying the duty cycle of a switching signal. Compared with conventional resistive or linear voltage regulation methods, PWM provides an efficient means of regulating motor speed with relatively low switching losses and can be readily implemented using embedded microcontrollers. In a DC motor drive, an increase in PWM duty cycle generally increases the average armature voltage and consequently the rotational speed. However, motor performance is also influenced by mechanical loading, where an increase in load torque typically results in higher armature current and may reduce the steady-state motor speed. These characteristics make PWM-controlled DC fan systems suitable platforms for investigating the interaction between electrical input variables and mechanical drive performance [3], [4].

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The integration of environmental sensing with embedded control further enables fan operation to respond automatically to changes in ambient conditions. Temperature-based fan controllers commonly employ microcontrollers together with temperature sensors to determine the required operating speed without continuous manual adjustment. Previous studies have demonstrated the feasibility of Arduino- and ESP-based fan controllers using temperature sensing and PWM regulation [1], [2]. Other studies have explored Internet of Things (IoT) connectivity to provide remote monitoring and control of household appliances, including electric fans [5]. Although IoT technology offers additional monitoring capabilities, a standalone embedded controller remains a practical and low-cost approach for implementing automatic fan speed regulation.

Despite the availability of various automatic fan control systems, many previous implementations have primarily focused on the functionality of temperature-based speed regulation. Comparatively less attention has been given to experimentally examining the electrical and mechanical behaviour of the fan drive under different PWM operating points and loading conditions. In particular, evaluating the relationships among PWM duty cycle, motor voltage, current consumption, rotational speed, and blade loading provides useful insight into the operating characteristics of a DC motor drive and its response to changes in mechanical load.

Therefore, this study presents the development and performance evaluation of an Arduino-based temperature-controlled variable-speed fan system. An Arduino Uno is employed as the main controller, while a DHT11 sensor provides ambient temperature measurements and PWM is used to regulate the DC fan motor through a motor driver circuit. The experimental evaluation investigates the relationships among PWM duty cycle, motor voltage, current consumption, and rotational speed. In addition, two different fan blade materials, namely laminated and hard paper, are evaluated to investigate the influence of blade loading on motor performance. Rather than claiming direct energy savings, this study evaluates the operating characteristics of the variable-speed drive and its potential to reduce unnecessary energy consumption by adjusting fan operation according to cooling demand. The findings provide an experimental basis for understanding the performance of a low-cost PWM-controlled DC fan drive and its potential application in automatic cooling systems.

2. LITERATURE REVIEW

2.1 Temperature-Based Automatic Fan Control

Temperature-based automatic fan control has been widely investigated as a practical approach for adapting cooling performance to changes in environmental conditions. Such systems generally integrate a temperature sensor with a microcontroller to continuously monitor ambient temperature and automatically determine the required fan operating speed. An Arduino-based automatic fan control system employing a DHT11 temperature and humidity sensor, where fan speed was adjusted according to the measured temperature [1]. The study demonstrated that integrating environmental sensing with embedded control can eliminate continuous manual speed adjustment and enable fan operation to respond directly to variations in ambient conditions.

More recent studies have extended this approach by incorporating additional sensing capabilities. A developed smart fan system combining temperature and motion detection to control fan operation according to both environmental conditions and user presence. These studies demonstrate the feasibility of low-cost sensor-based fan controllers for automatic cooling applications [4]. However, their primary emphasis was on control functionality, while detailed investigation of the electrical and mechanical characteristics of the DC motor drive under varying operating conditions received comparatively limited attention.

2.2 PWM-Based DC Motor Speed Control

Pulse Width Modulation (PWM) is commonly employed for DC motor speed regulation because it enables the average voltage supplied to the motor to be controlled by varying the duty cycle of a switching signal. The technique is particularly suitable for microcontroller-based applications because the required switching signal can be generated directly through digital control while maintaining relatively efficient motor operation.

In temperature-controlled fan applications, PWM allows the controller to assign different motor operating speeds according to predefined temperature ranges. A temperature-responsive DC fan control system using an ESP32 and PWM regulation and demonstrated that changes in PWM duty cycle produced corresponding changes in fan operating speed. From the perspective of DC motor drive behaviour, increasing the PWM duty cycle increases the effective voltage applied to the motor, which generally increases rotational speed. Motor current is also affected by mechanical loading because a higher load torque requires greater electromagnetic torque production. Consequently, simultaneous analysis of PWM duty cycle, voltage, current, and rotational speed provides a more comprehensive assessment of variable-speed fan drive performance than evaluating speed regulation alone [3].

2.3 IoT-Based Monitoring Systems

Advances in the Internet of Things (IoT) have enabled conventional household appliances to incorporate remote monitoring, wireless control, and real-time data acquisition. Yammen et al. [6] investigated an IoT-based fan control system in which fan operation and speed could be remotely controlled through wireless communication. Such systems demonstrate how connectivity can enhance user accessibility and provide additional monitoring capabilities beyond conventional standalone controllers.

Other studies have investigated the use of operational data from connected fan systems to understand energy consumption and environmental conditions [7]. The availability of real-time operating data can potentially support more advanced control strategies and energy management. Nevertheless, the addition of IoT connectivity increases hardware and software requirements and is not essential for implementing the fundamental temperature-based speed control function. Therefore, the present study focuses on a standalone Arduino-based controller, while IoT-based monitoring is considered a potential extension for future development.

2.4 Research Gap and Contribution

Previous studies demonstrate that temperature sensing, PWM-based motor control, and smart monitoring technologies can individually improve the functionality of electric fan

systems. However, much of the existing work has focused primarily on automatic fan operation, remote accessibility, or implementation of the control algorithm. Comparatively less attention has been given to experimentally evaluating the electrical and mechanical behaviour of a low-cost PWM-controlled DC fan drive under different operating and loading conditions.

To address this gap, the present study develops an Arduino-based temperature-controlled variable-speed fan system and evaluates the relationships among PWM duty cycle, motor voltage, current consumption, and rotational speed. In addition, two fan blade materials, namely laminated paper and hard paper, are experimentally compared to investigate the effect of blade loading on DC motor performance. This evaluation enables the influence of mechanical loading on current demand and achievable motor speed to be examined alongside the temperature-based PWM control function. The study therefore extends beyond functional prototype implementation by providing experimental insight into the electrical and mechanical operating characteristics of a low-cost variable-speed DC fan drive.

3. THE DEVELOPMENT OF THE TEMPERATURE-CONTROLLED VARIABLE-SPEED FAN SYSTEM

3.1 System Architecture

The proposed temperature-controlled variable-speed fan system was developed using an Arduino Uno as the main processing and control unit. The system comprises four principal stages: temperature sensing, control processing, motor driving, and output display. Ambient temperature is measured using a DHT11 temperature and humidity sensor and transmitted to the Arduino Uno. Based on predefined temperature ranges, the microcontroller determines the corresponding PWM duty cycle and generates a PWM control signal to regulate the DC fan motor through an L293D motor driver. A 16×2 I2C LCD is used to display the measured temperature and fan operating condition in real time.

The L293D serves as an interface between the low-power microcontroller output and the DC motor, allowing the Arduino-generated PWM signal to regulate the motor without directly supplying the motor current from the microcontroller. The control and motor drive stages are arranged to minimize the influence of motor switching and inductive disturbances on the low-power control circuitry. The overall functional architecture of the proposed system is illustrated in Figure 1.

3.2 Hardware Implementation

The prototype was constructed on a breadboard using an Arduino Uno, DHT11 sensor, L293D motor driver, DC motor with interchangeable fan blades, 16×2 I2C LCD, and a DC power source. The Arduino Uno executes the temperature-based control algorithm and generates the PWM signal required for motor speed regulation. The I2C LCD communicates with the Arduino through the SDA and SCL connections and provides a real-time indication of the measured temperature and fan operating condition.

The L293D motor driver is used to provide the required interface between the Arduino Uno and DC motor. The driver supports bidirectional motor operation through its internal H-bridge configuration; however, only the required rotational

direction is employed for the fan application. The PWM signal generated by the Arduino is applied to the motor drive stage to regulate the effective voltage supplied to the motor. The complete hardware configuration is presented in Figure 2. The original system document specifies the L293D as a high-current half-H driver and describes its internal H-bridge operation.

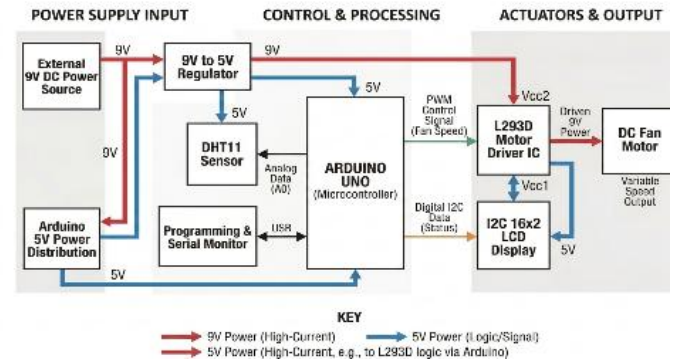


Fig. 1. Functional block diagram of the proposed temperature-controlled variable-speed fan system.

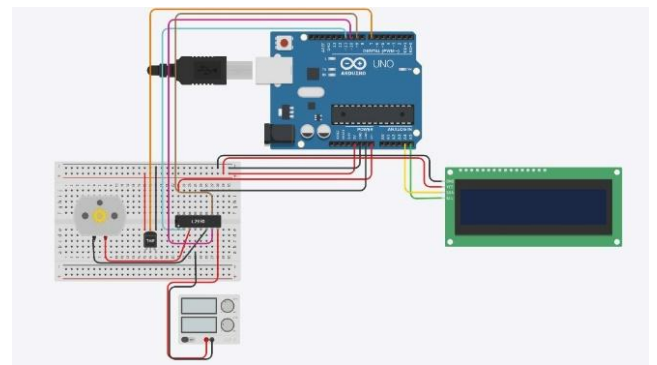


Fig. 2. Circuit diagram of the fan-controlled system.

3.3 Temperature-Based PWM Control Strategy

The rotational speed of the DC fan motor was regulated using Pulse Width Modulation (PWM) generated by the Arduino Uno through Digital Pin 9. The Arduino analogWrite() function provides an 8-bit PWM command ranging from 0 to 255, where a value of 0 represents a 0% duty cycle and 255 represents a continuous HIGH output. By varying the duty cycle of the switching signal, the effective voltage applied to the DC motor can be controlled, thereby regulating its rotational speed.

The PWM duty cycle, D , corresponding to the Arduino command can be expressed as

$$D = \frac{PWM \text{ value}}{255} \times 100\% \quad (1)$$

where D is the PWM duty cycle in percentage. Three PWM operating levels were implemented in this study, corresponding to low-, medium-, and high-speed fan operation, as summarized in Table 1.

Table 1. PWM operating conditions for DC fan speed control

Operating Condition	Arduino PWM Value	Approximate Duty Cycle (%)	Fan Operation
Low	64	25.1	Low-speed operation
Medium	127	49.8	Intermediate-speed operation
High	255	100.0	Maximum commanded operation

For an ideal PWM-controlled DC motor drive, the effective average voltage applied to the motor can be approximated by

$$V_{avg} \approx DV_s \quad (2)$$

Where V_{avg} is the average motor voltage, V_s is the DC supply voltage, and D is the duty cycle expressed as a decimal fraction. Therefore, increasing the PWM duty cycle generally increases the effective motor voltage and consequently increases the rotational speed.

In the implemented temperature-based control strategy, the Arduino continuously monitors the ambient temperature measured by the DHT11 sensor and assigns the corresponding PWM operating level according to the predefined temperature range. At low temperatures, a PWM value of 64 is applied to provide low-speed operation. As the temperature increases, the PWM command is increased to 127 for intermediate-speed operation and subsequently to 255 for the highest commanded speed. This control strategy allows the fan speed to adapt automatically to changes in ambient temperature rather than operating continuously at maximum speed.

It should be noted that the PWM duty cycle does not directly represent the percentage of motor power or torque. The actual electrical power and motor performance depend on the measured voltage, current, motor characteristics, motor-driver voltage drop, and mechanical loading conditions. Therefore, the motor voltage, current, and rotational speed were experimentally measured at each PWM operating level to evaluate the actual performance of the proposed DC fan drive system.

3.4 Experimental Procedure

The experimental investigation was conducted to evaluate the performance of the temperature-controlled DC fan drive under different PWM operating points and blade loading conditions. Following hardware assembly and functional verification, the system was operated at three predefined PWM duty cycles of approximately 25%, 50%, and 100%, corresponding to Arduino PWM commands of 64, 127, and 255, respectively. At each operating condition, the motor voltage, current, and rotational speed were measured and recorded.

To investigate the influence of mechanical loading, two different fan blade materials, namely laminated paper and hard paper, were installed separately on the DC motor. The same experimental procedure and PWM operating points were applied to both blade configurations to ensure a consistent comparison. The measured data were subsequently analysed to determine the relationships among PWM duty cycle, electrical characteristics, rotational speed, and blade loading.

3.5 Motor Speed Measurement

The rotational speed of the DC fan motor was measured using a digital optical tachometer. A reflective marker was attached to the rotating fan hub or blade surface, and the tachometer was directed towards the marker to detect each revolution through reflected light. Measurements were taken after the motor reached a steady operating condition at each PWM setting. The rotational speed was recorded in revolutions per minute (rpm) for each test condition, including the different PWM levels and blade loading configurations. The same measurement procedure was applied consistently for both laminated and hard paper fan blades to ensure a fair comparison of motor performance. The measured RPM values were subsequently used to evaluate the relationship between PWM duty cycle, motor current, and rotational speed.

3.6 Performance Evaluation

The performance of the proposed fan drive system was evaluated based on the measured motor voltage, current, rotational speed, PWM duty cycle, and blade loading condition. The electrical input power at each operating point was calculated as

$$P_{in} = VI \quad (3)$$

where P_{in} is the electrical input power in watts (W), V is the measured motor voltage in volts (V), and I is the measured motor current in amperes (A).

The experimental analysis focused on the relationships between PWM duty cycle and motor speed, PWM duty cycle and electrical input characteristics, and motor current and rotational speed under different blade loading conditions. Comparison between the laminated and hard paper fan blades was used to evaluate the influence of mechanical loading on the motor current and achievable rotational speed. In a DC motor, an increase in mechanical load generally requires higher electromagnetic torque and consequently greater motor current, which may result in a reduction in steady-state rotational speed. These relationships were used to assess the operating characteristics of the proposed PWM-controlled DC fan drive system.

4. RESULTS AND DISCUSSION

4.1 PWM-Based Motor Performance

Table 2 summarizes the measured voltage, current, and rotational speed of the DC fan motor at the three PWM operating conditions. The results demonstrate that increasing the PWM duty cycle produced a corresponding increase in motor speed. This behaviour is consistent with the operating principle of a PWM-controlled DC motor drive, where a higher duty cycle increases the effective voltage applied to the motor. Consequently, the motor develops a higher rotational speed as the PWM command is increased from the low-speed to the maximum commanded operating condition. An increase in motor current was also observed at higher operating points, indicating greater electrical input demand as the motor produced higher speed and overcame the aerodynamic resistance generated by the rotating fan blade. Overall, the measured trends confirm that PWM provides an effective means of regulating the operating speed of the proposed DC fan drive.

Table 2. Electrical and rotational performance of the DC fan motor at different PWM operating conditions

PWM Duty Cycle (%)	PWM Command	Voltage (V)	Current (A)	Speed (RPM)
25	64	2.5	0.11	7436.5
50	127	4.1	0.18	11381
100	255	5.4	0.27	14041

4.2 Relationship Between PWM Duty Cycle and Motor Speed

Figure 3 illustrates the relationship between PWM duty cycle and measured motor speed. A clear positive trend was observed, indicating that the rotational speed increased as the PWM duty cycle was increased. This response can be attributed to the higher effective voltage applied to the motor at higher duty cycles, which increases the steady-state motor speed. The experimental trend therefore agrees with the expected behaviour of a PWM-controlled DC motor drive. The results also demonstrate that the selected PWM operating points provide distinct low-, intermediate-, and high-speed operating regions, enabling the controller to adjust the fan speed according to the measured ambient temperature.

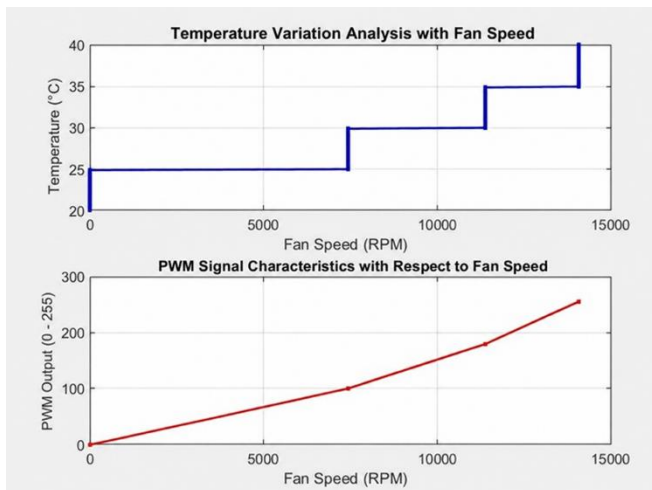
**Fig. 3.** Temperature vs Speed & PWM output vs Speed

Table 3 compares the performance of the DC fan motor using laminated and hard paper blades under the selected operating conditions. The results show that the blade configuration significantly influenced both motor current and rotational speed. Compared with the laminated blade, the hard paper blade generally resulted in lower rotational speed and higher current demand. At the highest operating condition, the laminated blade achieved approximately 14,041 rpm, whereas the hard paper blade reached 9,229.1 rpm, corresponding to a reduction of approximately 34.3% in rotational speed. The observed difference indicates that the hard paper blade imposed a greater mechanical and aerodynamic load on the motor.

From a DC motor-drive perspective, an increase in mechanical load requires greater electromagnetic torque to maintain rotation. Since developed motor torque is related to armature current, the increased loading condition results in greater current demand. Consequently, a larger portion of the available motor capability is required to overcome the blade

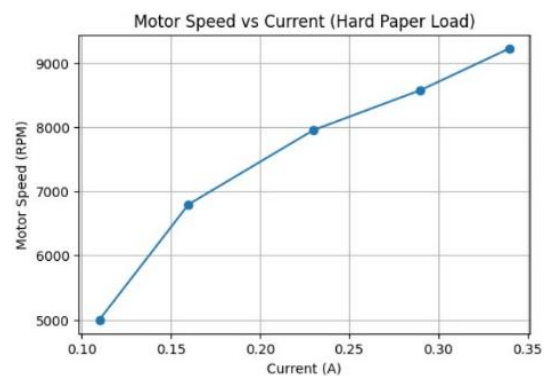
load, resulting in a lower achievable steady-state speed. These results demonstrate the interaction between mechanical loading, current demand, and rotational speed and provide experimental evidence of the expected load characteristics of a DC motor drive.

Table 3. Performance under different load conditions

Type of Blades	Load Condition	Current (A)	Speed (RPM)
Laminated	Low	0.11	7436.5
	Medium	0.18	11381
	High	0.27	14041
Hard Paper	Low	0.11	4997.1
	Medium	0.22	7411.0
	High	0.34	9229.1

4.3 Relationship Between Motor Current and Speed

Figure 4 shows the relationship between motor current and rotational speed under the hard paper blade loading condition. The measured current increased from approximately 0.11 A to 0.34 A, while the rotational speed increased from 4,997.1 rpm to 9,229.1 rpm as the PWM operating level was increased. The increase in current reflects the additional electromagnetic torque required to overcome the mechanical and aerodynamic resistance of the heavier blade configuration. Although both current and speed increased with the PWM command, the higher current should not be interpreted as the direct cause of the increase in speed. Instead, both parameters respond to the increased PWM excitation and the resulting motor operating point under load. The results therefore illustrate the combined influence of electrical input and mechanical loading on the steady-state performance of the DC fan motor.

**Fig. 4.** Motor Speed versus Current under Hard Paper Load Conditions

The calculated electrical input power increased with the PWM operating level, from approximately 0.275 W at the low-speed condition to 1.458 W at the highest operating condition. This trend is expected because both the effective motor voltage and current demand increase as the motor operates at higher speed. The results demonstrate that lower-speed operation requires substantially less electrical input power than maximum-speed operation. Therefore, temperature-based variable-speed control has the potential to reduce unnecessary energy consumption by avoiding continuous operation at the highest PWM setting when maximum cooling is not required. However, since the present study did not perform a time-based energy comparison against a conventional fixed-speed fan, the

results should not be interpreted as a direct measurement of energy savings.

Overall, the experimental results demonstrate that the proposed Arduino-based fan drive successfully provides distinct variable-speed operation through PWM control. Increasing the PWM duty cycle increases the effective motor voltage and rotational speed, while changes in blade loading influence the current demand and achievable steady-state speed. The comparison between laminated and hard paper blades further demonstrates that mechanical loading is an important factor in DC fan drive performance. These observations are consistent with established DC motor-drive behaviour and confirm that the developed prototype provides a practical platform for investigating the relationships among PWM control, electrical input characteristics, mechanical loading, and motor speed.

5. CONCLUSION

This study successfully developed and experimentally evaluated an Arduino-based temperature-controlled variable-speed fan system using PWM control. The Arduino Uno was employed to process the temperature measured by the DHT11 sensor and regulate the DC fan motor through predefined PWM operating levels. Experimental evaluation at approximately 25%, 50%, and 100% PWM duty cycles demonstrated that increasing the PWM duty cycle increased the effective motor voltage and rotational speed, which is consistent with the expected characteristics of a PWM-controlled DC motor drive. A maximum rotational speed of approximately 14,041 rpm was obtained under the laminated blade configuration.

The experimental results also demonstrated the influence of mechanical loading on motor performance. Compared with the laminated blade, the hard paper blade produced a lower maximum rotational speed of approximately 9,229.1 rpm, representing a reduction of approximately 34.3%. The hard paper blade also required a higher motor current, indicating greater torque demand due to the increased mechanical and aerodynamic loading. These findings demonstrate the relationships among PWM duty cycle, motor current, rotational speed, and blade loading in the developed fan drive system.

Overall, the developed system demonstrates a practical and low-cost approach to automatic temperature-based fan speed regulation. By adjusting the fan operating speed according to cooling demand, the proposed control strategy has the potential to reduce unnecessary energy consumption compared with continuous maximum-speed operation. However, direct energy savings were not quantified in this study. Future work may include closed-loop speed control, improved temperature sensing, optimized fan blade design, direct energy-consumption analysis, and IoT-based remote monitoring and control.

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