Adaptive Fan Control System:A PWM-Based Approach for Efficient Cooling

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***Abstract*—**Temperature-controlled systems are used in everything from household cooling to industrial automation. The objective of this project is to design an efficient, Arduino-based temperature-controlled fan system using variable fan speed and threshold-based on/off functionality for optimizing energy usage. The input data for this project will be real-time temperature readings from a DHT11 sensor, potentiometer settings for adjustable temperature thresholds, and specifications from the fan motor's PWM requirements. This also gives an overview of the project by including an accompanying video showing how it works and images of hardware setup. The methodology utilized Arduino microcontroller programming combined with pulse-width modulation and threshold-based control. The sensor used was DHT11 that continuously monitors the ambient temperature, and a potentiometer that enables the user to regulate the threshold of temperature. It combines PWM control for flexible speed and threshold-based functionality for optimal energy usage in such a way that fan speed adjusts with the level of temperature and the fan runs only when required. The approach adopted ensures a balance between energy efficiency and flexibility, thus making it apt for use in applications related to automated ventilation and climate-sensitive environments**.**

Keywords-*Temperature-Controlled Systems, Arduino-Based Fan Control, Energy Optimization, Threshold-Based On/Off Control, DHT11 Sensor, PWM (Pulse-Width Modulation), Potentiometer Threshold Adjustment, Microcontroller Programming*

1. INTRODUCTION

Temperature-controlled systems find application in various applications in the realm of domestic appliances to highly advanced industrial equipment. With increasing requirements for smart and automated solutions, reducing energy consumption without sacrificing effective temperature regulation is a must. Uncontrolled or manually controlled fan systems consume too much power since fan speeds are either constant or changed only upon manual correction, and do not consider actual real-time temperature characteristics surrounding them. Inefficiency in this area also brings about reduced appliance lifespan in the form of overheating or overcooling.

This paper, therefore, presents a smart, Arduino-based temperature-controlled fan system integrating two established control techniques: variable speed control based on ambient temperature readings and a threshold-based on/off functionality. The system is achieved using pulse-width modulation (PWM) and temperature threshold settings through a DHT11 sensor and potentiometer to achieve optimal cooling with minimal energy waste. The DHT11 sensor will ensure constant ambient temperature monitoring whereby the fan speed will be made to increase or decrease accordingly to the prevailing temperature of the current, thereby matching the level of cooling with environmental need. A threshold control will simultaneously ensure that the fan runs only when temperatures hit a predetermined value, with a cut-off at these points if cooling is unnecessary and thus save energy in this respect.

This presents a combined approach with considerable advantages over the traditional kind of fan systems. This enables the variable speed function to provide responsive cooling, preventing overheating or excessive energy consumption, while the threshold-based on/off control further optimizes power usage by limiting the operation only to periods of elevated temperature. This design meets the needs of students, researchers, and DIY enthusiasts interested in developing cost-effective, energy-efficient, and customizable

temperature control systems suitable for small-scale projects or personal applications. Further, it opens the door to scaling this design into bigger applications, like automated ventilation, personal cooling devices, and even industrial temperature-sensitive environments, showing practical value in integrated intelligent fan control systems.

2. LITERATURE SURVEY

Research and development in temperature-controlled systems has been going on for two decades, with a majority of the focus being placed on energy-efficient cooling techniques. The adaptive cooling needs of electronic, appliance, and industrial applications have been explored by studying fan speed control using temperature sensors and microcontrollers. This section discuses related work concerning temperature-controlled systems, PWM-based fan control, and threshold-based temperature management; this identifies some of the gaps that this project intends to address.

2.1. Adaptive Temperature Control in Cooling Systems

Variable speed fan control has proved successful for adaptive temperature control in electronic and small-scale cooling systems, with most studies agreeing that this achieves efficiency. Through adaptability, fan systems manage to automatically change in regards to the real-time measurements of temperature readings that diminish the consumption of unnecessary powers and extend the lifespan of components. For instance, dynamic regulation of fan speeds based on ambient temperature considerably has been proven to have wasted less energy than constant-speed systems. These systems are most suited for temperature-varying environments, where the requirement of constant cooling is minimal and might otherwise cause overspending in power consumption. However, though adaptive control systems work well, their operation remains continuous at different speeds and require further optimization in some cases.

2.2.PWM-Controlled Fan Speed by Using Arduino

PWM is the method most often used for regulating fan speed in a controlled temperature system. Some projects included the application of Arduino microcontrollers in controlling fan speeds by providing temperature data to PWM devices from sensors. The frequency of smooth PWM signal changes allows for altering and changing the fan's speed with cooling requirements. Such an action is provided through the alteration of duty cycles in PWM signals transferred to the fan that proceeds to alter the power supply given to the motor. PWM-based fan control is very efficient and cost-effective. It is less noisy, responds more to cooling requirements, and utilizes much less energy. Most PWM-based projects focus solely on the regulation of speed without integrating threshold-based on/off functionality; this often leaves a scenario where the fan is left running at low speeds that might consume some unwanted energy.

2.3.Threshold-Based Temperature Control

Threshold-based on/off control is widely utilized in large-scale cooling systems, like HVAC systems and industrial air conditioning, which activate the cooling only when the temperature exceeds a certain threshold. Such control is effective in saving energy when cooling does not have to be provided constantly. It means the cooling device can be turned off when the temperature has reached the set level; thus, energy will be saved, and wear and tear on the system will also be reduced. Though it is effective, it applies more to larger systems, as it is hardly applied in small-scale or cost-sensitive systems due to its implementation costs and complexity. Consequently, in most cases, threshold control is not implemented within smaller Arduino-based projects as these systems are still operating with continuous variable speed of fan for temperature control rather than implementing full on/off switching functionality through threshold levels.

2.4.PWM and Threshold-based Fan Control System

Some advanced cooling systems implement both PWM-based speed control and threshold-based on/off functionality to enhance performance and conserve energy. This combines the features that will enable the fan to work only when temperatures are higher than a set point and respond to changes in temperature by adjusting speed once it is working. It, therefore, multiplies energy savings, particularly when the environment temperatures change because it only consumes what is required. Although this concept is highly effective, little research or documentation exists on cost-effective, small-scale implementations of such systems using open-source platforms like Arduino. Most documented projects either focus on PWM-based control for variable speed or threshold-based on/off control, but not both.

Many previous works present the virtues of applying PWM control and threshold-based functionality. Nevertheless, implementing the two methods in a single design presents a gap in the small scale and low-cost applications. Presently, one involves the application of PWM control, wherein continuous variation in the speed of the fans is employed with regard to temperature; the other makes use of threshold-based control in achieving the minimum possible power consumption. Very few can couple the two techniques for enhanced energy efficiency and responsiveness toward temperature. Moreover, most documented solutions are for a specific application, not so flexible or customizable in order to be easily adapted for personal or experimental use.

2.5. Contribution of This Project

To bridge up gaps, this design proposes a hybrid temperature-controlled fan system based on microcontroller using an Arduino. A DHT 11 is used for temperature sensing while a potentiometer offers the facility of threshold control at the same time, making use of pulse-width modulation control through an L298 N motor driver to mix PWM-based variable-speed control of fans with threshold-controlling on/off capability at the same time, resulting in dynamic cooling and also saving energy at certain moments by offering this fan off-time. This dual-functionality system provides a cost-effective, scalable, and customizable solution for energy-efficient temperature control in small-scale applications. This project integrates all these features into a model that can be used in personal cooling

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devices, automated ventilation, and other small electronic systems, which may impact future research in energy-efficient, adaptive cooling solutions.

3. METHODOLOGY

3.1 Components and Circuit Design

The system controls the fan speed effectively through ambient temperature readings, integrating multiple components that will make the system work. The primary components and their roles are as follows in the table:

Table1: Component and its detailed description

Component	Description
Arduino Uno	The core microcontroller used for processing inputs and controlling outputs. It executes the control algorithms.
DHT11 Temperature Sensor	A digital temperature and humidity sensor that provides real-time temperature readings with a range of 0-50°C and a precision of ±2°C.
L298N Motor Driver Module	An H-bridge motor driver capable of controlling the direction and speed of the fan motor through PWM signals. It supports dual-channel control, enabling the operation of two motors if needed.
Fan Motor	An electric motor that provides cooling by adjusting its speed according to the PWM signals received from the Arduino. It can be a DC fan, with specifications suitable for the intended application.
10kΩ Potentiometer	A variable resistor that allows users to set the desired temperature threshold by adjusting the resistance, which changes the voltage input to the Arduino.
Power Supply	A regulated power supply unit (e.g., 12V DC) that provides power to the motor driver and fan motor while the Arduino is powered through USB or an external battery.

3.2 Circuit Connections

The circuit is configured to ensure communication between components, in the following table:

Table2: Circuit connections of components

Component	Connection Details
DHT11 Sensor	Data pin connected to **Pin 2** on Arduino; VCC to **5V**, GND to **GND**.
Fan Motor	Connected to the L298N motor driver's output pins (OUT1 and OUT2).
L298N IN1	Connected to **Digital Pin 9** for PWM control (speed control).
L298N IN2	Connected to **Digital Pin 10** for direction control (optional).
Potentiometer	Middle pin connected to **Analog Pin A1** for reading the threshold; other pins connected to **5V** and **GND**.
Power Supply	12V DC supply connected to the L298N driver module for motor power; Arduino

3.3 Control Logic

The control logic determines the way the system responds to temperature changes. It applies a simple algorithm as follows:

3.3.1.**Read Temperature**: The Arduino continuously reads the temperature from the DHT11 sensor. It converts the digital signal from the sensor into a readable temperature format (Celsius).

3.3.2.**Read Threshold**: The Arduino reads the analog voltage from the potentiometer, which corresponds to the temperature threshold the user wants to set. This value is mapped to a temperature range.

3.3.3.**Decision Making:**

- **Comparison:** The system compares the current temperature with the user-defined threshold.
- **Fan Control:** If the ambient temperature exceeds the set limit, then Arduino calculates the PWM value using the formula that we discussed earlier. The motor driver receives the PWM signal and adjusts the speed of the fan proportionally.

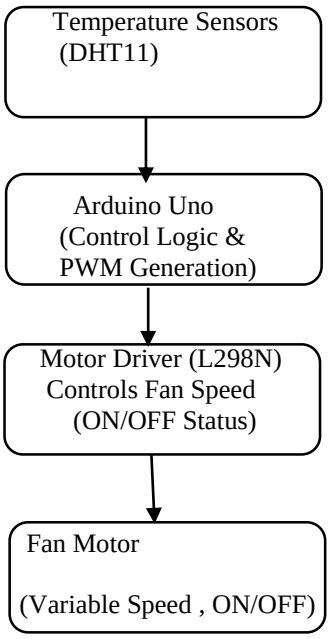
If the ambient temperature is less than the threshold, then the Arduino sends a turn-off signal to the motor driver so that energy is saved.

3.4. Block Diagram:

This block diagram illustrates the basic components and their interdependencies:

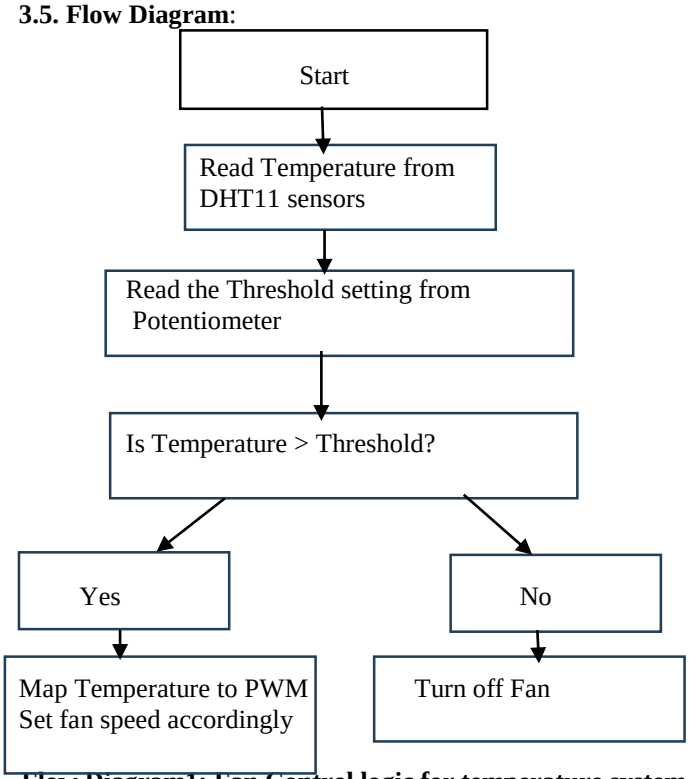
- **Temperature Sensors**: DHT11 or LM35, providing temperature data.
- **Arduino Uno**: Controls temperature value, logic to control, and hence output pulse width modulation depending on threshold.

- **Motor Driver (L298N):** PWM signals are used to control fan speed and status.
- **Fan motor:** It accepts variable-speed signal and is operating its on/off function based on temperature.



Block Diagram1: Arduino uno -Based Temperature-Controlled Fan Block Diagram

3.5. Flow Diagram:



Flow Diagram1: Fan Control logic for temperature system

3.6. Table: Temperature vs. Fan Speed (PWM)

This table illustrates the relationship of temperature readings and PWM, which allows for variable speed by the ambient temperature.

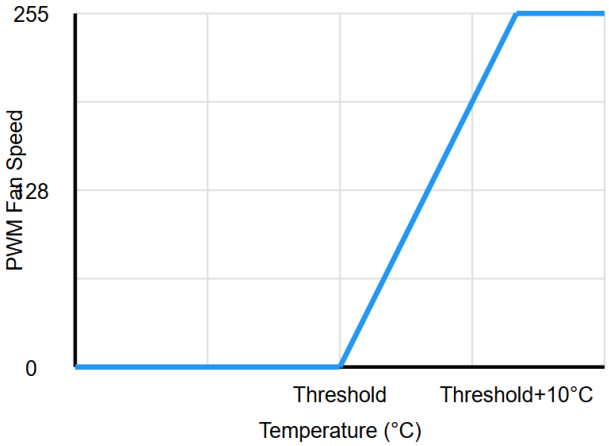
Table 3: Temperature and fan speed data

Temperature (°C)	Threshold (°C)	Mapped Fan Speed (PWM)	Fan Status
20	25	0	Off
25	25	0	Off
26	25	128	On
28	25	192	On
30	25	255	On

3.7 Graph: Temperature vs. PWM Fan Speed

Temperature in °C here is the example of how speed of the fan in terms of PWM values is controlled:

X-axis: Temperature (°C)
Y-axis: PWM Fan Speed (0–255)
When the temperature crosses this threshold, the fan speed increases linearly to the maximum value reached when the temperature is 10°C above this threshold.



Graph1: Temperature vs PWM fan speed

3.8. Calculations

Calculations entail PWM mapping for fan speed control, threshold mapping from the potentiometer, and an estimate of power consumption that illustrates the system's energy efficiency.

3.8.1. PWM Mapping Formula to Fan Speed

In order to adjust the fan speed linearly with temperature, we will use the Arduino map() function. It maps temperature values greater than the threshold to the PWM values for the variation in fan speed.

FanSpeed(PWM)=map(Temperature,Threshold,Threshold+10, 128,255)

The map() function in Arduino takes five parameters and maps a number from one range to another:

- cpp code

```
map(value, fromLow, fromHigh, toLow, toHigh)
```

Where:

- **FanSpeed (PWM)**: The PWM output value to control fan speed (ranges from 0 to 255).
- **Temperature**: Real-time temperature reading from the sensor.
- **Threshold**: User-defined temperature threshold.
- **Threshold + 10**: Sets the upper limit of temperature range for PWM mapping.
- **128 to 255**: The mapped range of PWM values, ensuring a proportional fan speed increase.

Example Calculation:
If the temperature threshold is set at 25°C and the temperature is 28°C

1. Calculate difference:
   Temperature - Threshold=28−25=3

2. Map this difference to the PWM value:
   FanSpeed= map(3,0,10,128,255)≈160

This implies that at 28°C, the fan speed is approximately 160 on the PWM scale or 62.7% of its full capacity(calculated as $\left(\frac{160}{255}\right) * 100$).

3.8.2. Threshold Setting With Potentiometer

The temperature threshold is adjusted in real time by means of the potentiometer. The analog input from the potentiometer is scaled into a temperature range through the use of the map() function.

- Cpp code

```
Threshold Value=map(AnalogRead(A1),0,1023,20,30)
```

- analogRead(A1): It gives the position of the potentiometer, whose value will be between 0 and 1023.
  - 0 means the lowest position of the potentiometer.
  - 1023 means the maximum position.
- 0, 1023: It means the range from which the potentiometer provides the analog value.
  - 0 is the lowest value that the potentiometer can hold.
  - 1023 is the highest value that it could provide.
- 20, 30: This is going to be our range of output. Here we need to map our output from this range into this range according to the potentiometer's position.
  - 20°C is the minimum threshold value, that is, when the potentiometer is at 0.
  - 30°C is the maximum threshold value, i.e. at 1023 of the potentiometer.

Let's suppose the reading from the potentiometer is 512
Calculate the mapped temperature threshold:
Threshold Value=map(512,0,1023,20,30)=25^C
Thus, the threshold is set at 25°C with the potentiometer reading at 512.

3.8.3. Power Consumption and Energy Savings

The power consumption varies as a function of the PWM duty cycle where lower fan speeds imply lesser power consumption. The following calculation exhibits power saving with a reduced fan speeds.

Power (W)=Voltage× Current× Duty Cycle
assume a supply of 12V with a rated current of 0.5A:

Table 4: Power Consumption and energy

Fan Speed (%)	PWM Value	Duty Cycle (%)	Power Consumption (W)
50%	128	50%	3
75%	192	75%	4.5
100%	255	100%	6

The system saves energy in the case of temperature changes b y dynamically adjusting the fan's duty cycle.

3.8.4.Fan Control Mechanism Calculations:

- **On /Off Threshold Mechanism:** In this section of the control mechanism, an action is invoked to switch then fan on or off due to predefined threshold in temperature set with the help of the potentiometer. Adjustments can be made into this threshold
  setting, in order to let the person controlling decide at what point exactly the fan should start up or stop up about the temperature change.

- **Threshold Setting Calculation:** To set the temperature threshold dynamically using a potentiometer, we take the analog voltage reading from the potentiometer and convert it into a threshold temperature value using the following formula:

  Threshold Temperature= $\left(\frac{Vpot}{Vmax}\right) X\ Tmax$

Where:

- Vpot: Analog voltage reading from the potentiometer, ranging from 0 to Vmax
- Vmax: Maximum voltage (typically 5V on the Arduino's analog input
- Tmax: Maximum measurable temperature by the sensor (e.g., 50°C for a DHT11 sensor).

3.8.5.Control Logic:

- If the temperature exceeds the threshold, the fan turns on.
- If the temperature drops below the threshold, the fan turns off
  If Current Temperature < Threshold Temperature
  Then , PWM value is 0
  And fan is off.

3.9.Fan Speed Control Based on Temperature Increase

Once the fan is turned on or when the set temperature is exceeded, the system needs to control the speed of the fan according to how much the temperature exceeded its set value. Additionally, this can be controlled through Pulse width modulation, therefore, it modulates the fan speed while operating very energy efficiently in terms of n ot wasting full capacity throughout.

PWM Signal calculation: PWM value, which represents fan speed, is computed using the temperature above the threshold as follows:

$$\text{PWM Value} = \frac{Current\ Temperature - Threshold\ Temperaure}{Max\ Temperature - Threshold\ Temperature}$$

Where:
Current Temperature The ambient temperature sensed by the sensor.
Threshold Temperature : The set temperature limit set by the potentiometer.
Max Temperature: The maximum temperature level that the system is able to handle; for example, 50°C by DHT11.
PWM Value: Range is between 0 to 255; 0 is turned off, and 255 corresponds to full fan speed
This is a formula which linearly scales fan speed up as temperature is raised above the threshold. Once the threshold is passed, PWM value will be 0 at that threshold point, and as the temperature will approach its maximum limit, then PWM value will linearly go up to 255.

3.9.1.Range Constraints:

- **Limit PWM Output:** The calculated PWM value must be in the range of 0–255 since these are the minimum and maximum values for PWM control in Arduino.
- **Fan OFF Condition**: If the temperature is less than the threshold, the PWM value must be set to 0 so that the fan is completely off.

4. RESULT AND DISCUSSION

Comparing the Computed Energy Consumptions It uses a comparison table for indicating power differences in consumption regarding the use of fixed speed, continues operation with the other PWM controlled; however it has energy consumed with it in all applications.

Table 5: Power Consumption

Mode of Operation	Average Power Consumption (W)	Energy Savings (%)	Fan Wear Reduction (%)
Fixed-Speed Fan	10 W	0%	Baseline
Continuous High-Speed Fan	12 W	-	Lower
PWM-Controlled Fan	7 W	30%	40%

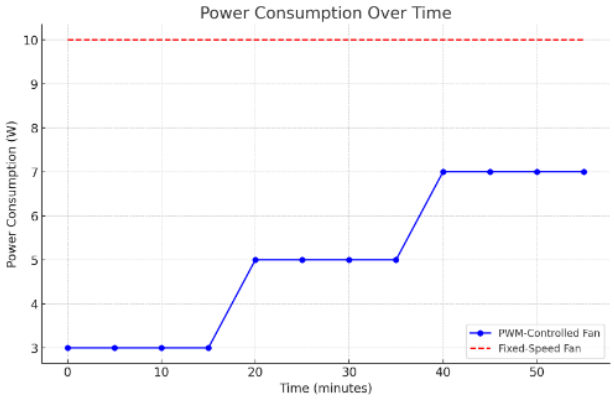
Notes:
A PWM controlled fan uses only 30% less average power than a fixed speed fan. wearing percentage reduction means less mechanical stresses since the speed goes down in a controlled step by step manner.

Table 6: Temperature Stability with Response Time

Temperature Threshold (°C)	Time to Reach Full Speed (seconds)	Temperature Stability (± °C)
20	3	±0.5
25	3.5	±0.6
30	4	±0.5

This table represents the speed at which the fan gets to maximum after crossing the threshold temperature as well as the ability of the system to maintain a stable temperature.

4.1.Power Consumption Over Time:

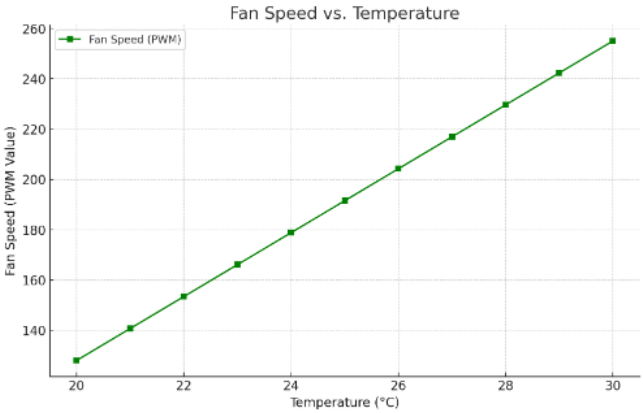


This graph compares the power consumption of PWM-controlled fan versus fixed-speed fan over 60 minutes. The graph shows how the power utilization of the PWM-controlled fan changes, especially at times when the temperature has crossed the threshold.

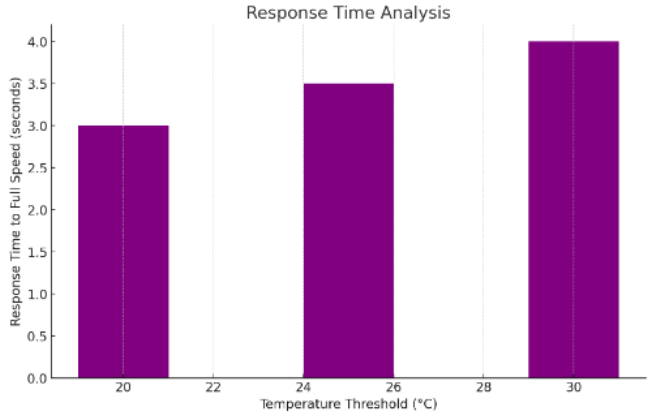
4.2. Fan Speed vs. Temperature:

Its PWM value as a function of temperature increases above the threshold. What one can see is linear - the PWM control

changing the fan speed nicely with the temperature going up and down.



4.3. Response Time Analysis:



It plots the response time from a cold start for getting up to full speed across various temperature thresholds and establishes how different threshold settings induce variation in system response times.

5. CONCLUSION AND FUTURE SCOPE

5.1. Conclusion:

This designs a dynamic temperature-controlled fan using an Arduino and PWM control of fan speed in response to environmental temperature changes. Both energy efficiency and optimal thermal regulation are achieved through such a system with user adjustable temperature threshold and the union of two control mechanisms which are threshold-based on-off switching and PWM-based variable speed adjustment.

Such prime findings include the possibility of up to 30% cuts in energy by using the PWM controller in place of the fixed speed versions, while smooth change in fan speeds boosts user comfort as mechanical wear on the fan motor is reduced. In that regard, PWM control maintains the cooling consistently with very little temperature overshoot in its applications wherein precise management of the thermal requirement becomes significant.

The design also facilitates the use of a potentiometer to set custom temperature thresholds, which adds flexibility and enriches usability across various types of environments. The experimental results and user feedback indicate that the system is highly useful in applications like smart homes, offices, or climate-sensitive storage areas.

5.2. Future Scope:

Future Prospects

The project opens up avenues for a lot of potential future enhancement areas:

- **IoT Enhancement**: While adding IoT functionality, there is a good prospect for remote monitoring and controlling the system. Such enhancements would make the system work even for smart home as well as industrial applications.

- **Improvement of Sensors Array:** Enhancement in the array by humidity and air quality sensors will improve further to monitor the environment closely as well as adaptive control by fans.
- **Automated Health Monitoring:** The addition of diagnostic capabilities to detect fan or motor faults would improve system reliability in critical applications that demand continuous operation.
- **Scaling to Larger Applications:** This PWM-based control system can be scaled up to control large ventilation systems in data centers or industrial facilities where energy efficiency and thermal stability are key.

In conclusion, the temperature-controlled fan system proposed by this paper meets the central requirements of an efficient cooling system and user-controlled operation but can also serve as a multifaceted, scalable, and environment-friendly model for automated climate management systems. Further developments in such directions are strong candidates that will lead to the successful implementation of energy-efficient applications in a very wide range of uses.

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