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Comparative analysis of microcontroller-based DC motor speed control techniques for industrial and household applications

Anggit Pamungkas[1], Mohd Hatta Jopri[2]
[1]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia
[2]Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia

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ABSTRACT

DC motors remain relevant in industrial equipment and household appliances because their speed can be regulated through relatively straightforward power-electronic interfaces. The increasing availability of low-cost microcontrollers has enabled conventional open-loop methods to evolve into closed-loop and intelligent control systems. However, selecting an appropriate technique requires balancing speed accuracy, disturbance rejection, implementation complexity, cost, and operating conditions. This review compares pulse-width modulation (PWM), proportional-integral-derivative (PID), adaptive PID, and fuzzy logic control, with particular attention to their implementation using microcontrollers. The reviewed studies indicate that PWM is an effective actuation method, while feedback and intelligent algorithms improve regulation when operating conditions vary. The most appropriate solution depends on the performance requirements and constraints of the intended application rather than on algorithmic complexity alone.

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1. INTRODUCTION

DC motors are widely used in applications that require controllable rotational speed, including conveyors, laboratory equipment, small production machines, fans, pumps, toys, and household appliances. Their speed can be adjusted by changing the voltage applied to the armature or by modifying the magnetic field, depending on the motor configuration and operating range. The development of embedded microcontrollers has made digital speed regulation increasingly practical because a single controller can process sensor signals, execute control algorithms, and generate switching commands for a motor driver. These capabilities provide opportunities to develop compact and economical control systems for both industrial and domestic environments.

Despite these advantages, maintaining a desired motor speed is not always straightforward. Changes in mechanical load, supply voltage, friction, and motor parameters can cause the actual speed to deviate from its reference value. A simple open-loop controller may be sufficient when the load is relatively constant, but it cannot automatically compensate for disturbances that affect motor speed. More demanding applications therefore require feedback mechanisms and control algorithms capable of correcting speed errors during operation.

Several approaches have been reported for microcontroller-based DC motor speed regulation. pulse-width modulation (PWM) provides an efficient means of adjusting the average voltage delivered to the motor, whereas proportional-integral-derivative (PID) control uses feedback to reduce the difference between reference and measured speeds. Adaptive PID and fuzzy logic approaches have also been investigated to address nonlinear behavior and changes in operating conditions [1]–[5]. This review addresses three related questions: how these techniques differ in their control mechanisms, what trade-offs they introduce in microcontroller implementation, and which approaches are most appropriate for industrial and household applications.

2. REVIEW SCOPE AND CONTROL-SYSTEM STRUCTURE

This review focuses on publications available up to 31 December 2015 that discuss DC motor speed regulation, digital control, or microcontroller-based implementation. The selected literature includes experimental systems using microcontrollers, application-oriented PWM implementations, and studies evaluating conventional or intelligent control algorithms. These sources provide complementary evidence, although their experimental conditions and motor configurations are not identical. Consequently, the comparison is qualitative and does not treat numerical results from different studies as if they had been obtained under a common test procedure.

A typical microcontroller-based speed-control system consists of a reference input, a controller, a motor driver, a DC motor, and a speed-measurement device. The reference input specifies the desired operating speed, while the sensor provides information about the motor's actual rotational speed. The microcontroller processes the measured information and determines the switching command delivered to the power stage. Depending on the selected method, the controller may operate without speed feedback or continuously adjust its output to minimize the speed error.

The motor driver is an important part of this architecture because a microcontroller pin cannot directly supply the current required by most DC motors. A transistor, MOSFET-based switching stage, or integrated H-bridge can provide the necessary power interface, while also supporting direction control when required. The driver must be selected according to motor voltage, starting current, operating current, switching frequency, and thermal requirements. Therefore, the performance of a speed-control system depends not only on its algorithm but also on the quality and suitability of its sensing and power-electronic components.

3. COMPARATIVE ANALYSIS OF SPEED-CONTROL TECHNIQUES

3.1. PWM-based open-loop control

PWM is one of the most widely used methods for regulating DC motor speed with a microcontroller. The technique controls the effective voltage applied to the motor by changing the proportion of each switching period during which the power device is turned on. A microcontroller can generate the required switching signal through a hardware PWM peripheral or a software-based routine, while a driver amplifies the signal to operate the motor. This approach is relatively simple, economical, and suitable for applications in which precise speed regulation is not essential.

Microcontroller-based PWM implementations have been demonstrated using different platforms and motor configurations. Papalkar and Phulambrikar [1] described a PIC-based approach that uses the microcontroller's capture, compare, and PWM peripheral to generate the switching signal. Royan and Luqman [2] applied an ATmega32-based PWM system to a DC shunt motor used in a laboratory shaker, demonstrating the practical use of programmable speed settings and timer-based operation. These examples illustrate the suitability of PWM for compact equipment where cost and straightforward operation are important design considerations.

The principal limitation of open-loop PWM is its inability to detect and correct speed deviations automatically. When the mechanical load increases, the motor may slow down even though the PWM duty cycle remains unchanged. Similar deviations may occur when the supply voltage changes or the motor operates under different temperature conditions. Consequently, open-loop PWM is more appropriate for applications with predictable loads than for processes requiring consistent speed under varying operating conditions.

3.2. Closed-loop PID control

Closed-loop PID control improves speed regulation by using feedback from a speed sensor. The microcontroller compares the measured speed with the reference value and processes the resulting error through proportional, integral, and derivative actions. The controller then adjusts the PWM command to reduce the speed deviation. This arrangement can compensate for load disturbances more effectively than an open-loop method, provided that the sensor, sampling process, and controller parameters are appropriately designed.

Mondal *et al.* [3] presented an embedded closed-loop DC motor speed-control system based on an 8051 microcontroller. Their implementation used a tachogenerator to measure motor speed and a proportional control algorithm to regulate the motor through an SCR-based power-control arrangement. The study is relevant to industrial applications because it demonstrates the use of a microcontroller and measured speed feedback in a system intended for applications such as electric vehicles and transport equipment. It also illustrates that feedback control does not necessarily require a computationally complex algorithm.

PID control is attractive because its structure is familiar, its computational requirements are generally manageable, and its parameters can be adjusted to obtain a desired response. Nevertheless,

controller tuning can be challenging when the motor operates over a wide speed range or experiences substantial changes in load. Poorly selected parameters may produce excessive overshoot, slow settling, or sustained oscillation. Practical implementations should also consider output saturation, measurement noise, sampling time, and integral windup, particularly when the motor driver has a limited operating range.

3.3. Adaptive PID control

Adaptive PID control seeks to improve conventional PID performance by modifying controller parameters according to operating conditions. A fixed-gain PID controller may perform satisfactorily around one operating point but provide a different response when the reference speed or load changes. Adaptive methods address this limitation by scheduling or adjusting controller gains across different operating regions. This approach can be useful when the motor operates under a wider range of conditions than a fixed-parameter controller can handle effectively.

Nurba *et al.* [4] investigated adaptive PID control using a gain-scheduling approach for DC motor speed regulation. Their reported results included a rise time of approximately 0.9 seconds, with no overshoot or steady-state error in the tested trajectory and a small oscillation of approximately 1 rpm. These results suggest that gain scheduling can improve the consistency of a PID controller across operating conditions. However, the reported performance should be interpreted within the limits of the specific motor, controller design, and experimental conditions used in that study.

A microcontroller can implement adaptive PID by selecting controller parameters from a predefined operating map or by updating them through a suitable adaptation procedure. The additional computation and memory requirements are generally higher than those of fixed-gain PID, although they remain feasible for many embedded platforms. The main design challenge is ensuring that parameter adaptation remains stable and does not introduce abrupt control changes. For industrial applications with changing loads and speed references, adaptive PID may offer a useful compromise between conventional feedback control and more complex intelligent methods.

3.4. Fuzzy logic control

Fuzzy logic control provides an alternative when an accurate mathematical model of the motor is difficult to obtain or when its operating behavior is affected by nonlinearities. Instead of relying exclusively on fixed controller gains, a fuzzy controller uses linguistic rules to determine the control action from input variables such as speed error and the change in speed error. The resulting control command can be converted into a PWM signal by the microcontroller. This approach allows control behavior to be designed using qualitative knowledge of the system, although the membership functions and rule base still require careful development.

Nadhif and Suryono [5] implemented a Mamdani fuzzy logic controller on an ATMega8535 microcontroller for DC motor speed regulation. Their system used a photodiode-based speed measurement arrangement and processed speed error and its change to generate a PWM command. The study provides direct evidence that fuzzy logic can be implemented on a relatively low-cost microcontroller rather than being limited to computer simulation. It also demonstrates the potential of fuzzy control in compact applications such as a line-following robot.

A further development is the combination of fuzzy logic with PID control. Akbari-Hasanjani *et al.* [6] examined a self-tuning fuzzy PID algorithm for a separately excited DC motor. Their approach adjusts PID parameters according to variations in operating speed, with the objective of improving transient response and reducing overshoot and settling time. The study used MATLAB/Simulink-based simulation, so its results should not be interpreted as direct proof of implementation on a microcontroller. Nevertheless, it provides a relevant control-design direction for embedded systems in which computational resources permit more advanced algorithms.

4. COMPARISON FOR INDUSTRIAL AND HOUSEHOLD APPLICATIONS

The suitability of each technique depends on the required speed accuracy, load variation, operating duration, safety requirements, and available implementation budget. Industrial systems commonly require reliable operation under changing mechanical loads, predictable response to disturbances, and the ability to integrate with supervisory control or monitoring equipment. Household applications often prioritize low cost, compact size, ease of use, low noise, and adequate performance under relatively predictable loads. These differences mean that the most sophisticated controller is not automatically the most appropriate choice for every application.

The principal characteristics of the reviewed techniques are summarized in Table 1. The comparison considers feedback requirements, implementation complexity, disturbance response, and typical application

suitability rather than assigning universal numerical performance rankings. Such a qualitative comparison is more appropriate because the reviewed studies use different motors, sensors, power stages, and experimental conditions. The table should therefore be interpreted as an engineering selection guide rather than as a direct experimental ranking.

Table 1. Comparison of microcontroller-based DC motor speed-control techniques

Control technique	Feedback requirement	Implementation complexity	Main advantages	Main limitations	Suitable applications
Open-loop PWM	Not required	Low	Low cost, simple implementation, efficient voltage adjustment	Cannot automatically compensate for load or supply changes	Fans, toys, simple pumps, small household equipment
Closed-loop PID	Speed sensor required	Moderate	Good speed regulation, established design procedure, manageable computation	Requires tuning and attention to sensor noise and saturation	Conveyors, laboratory equipment, small industrial drives
Adaptive PID	Speed sensor required	Moderate to high	Can accommodate changes in operating point and improve response consistency	More complex parameter design and validation	Variable-load drives and industrial equipment
Fuzzy logic	Usually requires feedback for speed regulation	Moderate to high	Can handle nonlinear behavior and incorporate qualitative control knowledge	Rule-base and membership-function design require expertise	Robotics, small automation systems, variable operating conditions
Fuzzy-PID	Speed sensor required	High	Combines PID structure with adaptive or rule-based adjustment	Greater design and computational effort; hardware validation is necessary	Applications requiring improved dynamic response and flexibility

As indicated in Table 1, open-loop PWM is the most economical choice when speed variation caused by load disturbances is acceptable. Closed-loop PID is generally more appropriate when a defined speed must be maintained despite moderate changes in load. Adaptive PID and fuzzy logic become attractive when motor behavior varies significantly or when conventional controller tuning does not provide satisfactory performance. However, their additional design effort should be justified by measurable improvements in the intended application.

For industrial applications, closed-loop PID is a practical starting point because it offers a structured method for reducing speed error and can be implemented on many microcontrollers. Adaptive PID may be preferable when the motor operates across multiple speed ranges or experiences substantial load variations. Fuzzy logic may be considered when nonlinear behavior and uncertain operating conditions make fixed-gain control less satisfactory. In all cases, industrial deployment requires attention to electrical protection, thermal management, electromagnetic interference, sensor reliability, and maintenance requirements.

For household applications, open-loop PWM may be sufficient for devices such as simple fans, toys, and low-cost appliances with relatively predictable operating conditions. More accurate regulation may be necessary for equipment such as laboratory shakers, small pumps, or appliances whose performance depends on maintaining a particular speed. The laboratory shaker implementation reported by Royan and Luqman [2] illustrates how PWM-based microcontroller control can support a dedicated household-scale or laboratory-scale device. Voice-command control using Arduino, as investigated by Birdayansyah [7] further illustrates how a microcontroller can combine speed regulation with a user-oriented interface.

The choice of a control algorithm should also consider the cost and reliability of the speed sensor. A tachogenerator or encoder can provide useful speed information, but it increases hardware cost and may require additional signal conditioning. Optical sensing can provide a relatively economical alternative, although its performance depends on sensor placement, mechanical alignment, and the quality of the detected signal. For low-cost household equipment, the additional expense of closed-loop control should therefore be evaluated against the practical benefit of improved speed stability.

5. RESEARCH CHALLENGES AND DESIGN CONSIDERATIONS

A major challenge in microcontroller-based motor control is the difference between theoretical controller performance and the behavior of a complete physical system. Simulation models may not fully represent friction, mechanical backlash, switching losses, sensor imperfections, supply fluctuations, or variations between individual motors. A controller that performs well in simulation may therefore require further tuning when transferred to embedded hardware. Experimental validation under representative operating conditions is essential before a design is adopted for industrial or household use.

Another important issue is the selection of the microcontroller and power stage. The controller must provide adequate processing capability, timer resolution, PWM frequency, input capture functions, and analog or digital interfaces for the selected sensors. The power stage must withstand starting current and transient loading without excessive heating or electrical stress. Designers should also include appropriate protection against overcurrent, reverse polarity, overheating, and electrical noise, particularly in systems that operate continuously or near users.

Future development should emphasize fair experimental comparisons using common test conditions. Researchers should evaluate rise time, settling time, overshoot, steady-state error, speed regulation under load changes, energy consumption, and implementation cost using the same motor and power stage. Hardware-in-the-loop testing and measurements on physical prototypes would improve the reliability of comparisons between PID, adaptive PID, and fuzzy logic methods. Such studies would help determine whether the additional complexity of an intelligent controller produces practical benefits over a well-tuned conventional controller.

6. CONCLUSION

This review compared four principal approaches to microcontroller-based DC motor speed regulation: open-loop PWM, closed-loop PID, adaptive PID, and fuzzy logic control. PWM provides a simple and economical method for adjusting motor speed, but open-loop operation cannot automatically compensate for changes in load or supply voltage. Closed-loop PID improves speed regulation through feedback and remains a practical choice for many industrial and household applications. Adaptive PID and fuzzy logic offer additional flexibility for nonlinear or variable operating conditions, although they require more design effort and careful validation.

The comparison indicates that control-system selection should be based on the operating requirements rather than on algorithmic sophistication alone. Open-loop PWM is suitable for cost-sensitive applications with relatively predictable loads, while closed-loop PID is a strong general-purpose option when speed accuracy is important. Adaptive PID and fuzzy logic are promising alternatives for applications that require improved response across changing operating conditions, provided that their additional complexity is justified. Ultimately, reliable motor speed control depends on the coordinated design of the control algorithm, microcontroller, speed sensor, motor driver, and protection system.

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