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Development of an Adaptive Speed Control System for Pedal-Assisted Electric Bikes

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ABSTRACT **Original research paper**

This paper presents the development and experimental validation of an adaptive speed control system for pedal-assist electric bicycles (e-bikes). Conventional e-bikes, which rely on fixed assistance levels, often provide a suboptimal riding experience. To address this, we designed a system centered on a Fuzzy-Proportional-Integral (Fuzzy-PI) controller. This system leverages real-time data from a torque sensor and a speed sensor to dynamically adjust the motor's power output, aiming to maintain a rider-set target speed seamlessly. The prototype e-bike, built around a 500W motor and an STM32F4 microcontroller, was tested against a conventional PI controller. Results demonstrate that the adaptive Fuzzy-PI system offers superior performance, including faster response to load changes (~0.1s vs. ~0.3s settling time), minimal speed overshoot (<2% vs. >7%), and improved energy efficiency. This research confirms that intelligent, adaptive control can significantly enhance rider comfort, safety, and battery life in personal mobility solutions.

Keywords: Pedal-assist e-bikes, Adaptive control, Fuzzy logic, Model predictive control, Sensor fusion, Energy efficiency.

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1. Introduction

1.1 Background of the Study

The global transportation sector is undergoing a significant transformation driven by the dual imperatives of sustainability and urban mobility. Within this landscape, electric bicycles (e-bikes) have emerged as a cornerstone of intelligent transportation systems, offering a compelling blend of physical activity, accessibility, and reduced environmental impact. Pedal-assisted e-bikes, which augment human pedaling effort with electric motor power, are particularly popular as they lower the barrier to cycling, extend commuting range, and make challenging terrain more accessible.

Despite their growing adoption, a critical technological limitation persists in most commercial pedal-assist systems. Conventional designs typically operate on static, pre-programmed assistance curves, often triggered solely by pedaling cadence. This "one-size-fits-all" approach provides a fixed level of motor power regardless of dynamic riding conditions, leading to a suboptimal and often disjointed user experience. As noted by industry analyses, a rider navigating a steep incline or battling a headwind may receive insufficient assistance, causing unnecessary physical strain (eMovement, 2024). Conversely, the same assistance level can feel abrupt and overpowered on flat terrain or downhills, undermining the natural, intuitive feel of cycling. This inability to adapt to the dynamic interplay between rider effort, terrain, and environmental conditions represents a significant gap in current e-bike technology (Kazemzadeh, 2021).

To bridge this gap, recent research has explored more sophisticated control strategies. While torque sensors offer an improvement by providing proportional assistance, they still lack the holistic context-awareness required for optimal performance. Advanced control theories, including Fuzzy Logic Control (FLC) and Model Predictive Control (MPC), have been identified as promising pathways toward creating more intelligent and responsive systems (Kaya & Demiroglu, 2024; Chen et al., 2021). These methods move beyond rigid, linear control, allowing for decision-making that mimics human intuition and can adapt to complex, non-linear systems in real-time.

This paper therefore presents the design, implementation, and validation of a novel adaptive speed control system for pedal-assist e-bikes. The core of our contribution is a hybrid Fuzzy-PI controller that leverages real-time sensor fusion to dynamically adjust motor assistance. By continuously monitoring rider-generated torque and actual vehicle speed, the system intelligently modulates the motor's power output to maintain a rider-defined target speed, seamlessly compensating for external disturbances such as hills and wind.

2. Review of Related Literature

Research into electric pedal-assist bicycles (e-bikes) shows a clear shift from basic static assistance toward more sophisticated adaptive control strategies that aim to enhance rider experience, efficiency, and safety. Early e-bike systems used simple cadence sensors, which provide consistent power output when a rider pedals, regardless of the force applied (eMovement, 2024; Heybike UK, 2024). While cost-effective, this approach is often criticized for its unnatural feel and poor responsiveness to dynamic changes in terrain or rider effort. Torque-sensing technology, which measures the force applied to the pedals to deliver proportional assistance, emerged as an advanced alternative, offering a more intuitive and responsive ride, though at a higher cost. The trade-offs between these two sensor types highlight the need for intelligent systems that can adapt to changing conditions and rider intent. To address these limitations, recent studies have explored more intelligent control methods, such as fuzzy logic control (FLC), to create a more adaptable and comfortable ride. FLC and self-tuning fuzzy logic controllers have been implemented to dynamically adjust assistance levels based on factors like rider input and road conditions, improving comfort and safety across diverse riding scenarios (Kaya & Demiroglu, 2024; MDPI, 2024). Complementary research has focused on adaptive control using proportional-integral (PI) controllers and disturbance observers, which can estimate external loads like road slope in real-time to adjust motor power accordingly. These approaches, along with human-centered algorithms that model rider biomechanics, represent a collective effort to move beyond static control toward dynamic, context-aware systems that provide a more natural, efficient, and intuitive pedal-assist experience.

3. Methodology

This section details the systematic approach used to design, implement, and validate the adaptive speed control system for a pedal-assist e-bike. The methodology is structured into three main phases: Hardware Design and Integration, Software Development and Control Algorithm, and Experimental Validation.

3.1 Hardware Design and Integration

The fabrication of the e-bike requires a combination of readily available parts and specialized electric components.

1. DC hub motor: The motor is having 500 watt. Capacity with maximum 2100 rpm. Its specifications are as follows: Current Rating: 7.5amp, Voltage Rating: 48, Volts Cooling: Air – cooled, Bearing: Single row ball.

Figure 1: DC Motor

2. Frame: The Frame is made up of Mild steel along with some additional light weight components. The frame is designed to sustain the weight of the person driving the unit, the weight of load to be conveyed and also to hold the accessories like motor. It is drilled and tapped enough to hold the support plates.

3. Lithium-ion Battery: Lithium-ion batteries are commonly used for portable electronics and electric vehicles. The type used is the LIFEPO4 type of battery pack with a Battery Management System (BMS). Rating of the battery 60V and capacities 40Ah, Lithium-ion (Li-ion) battery.

Figure 2: Lithium-ion Battery

4. Motor controller: The motor controller is considered to be the heart of the electric bicycle as it controls the amount of power required to drive the hub motor. It consists of transistors and microprocessor that detects any defects in functioning of hall sensors and to protect against any high or low voltage problems.

5. Chain Drive: Chain is an array of links held together with each other with the help of steel pins. This type of arrangement makes a chain more enduring, long lasting and better way of transmitting rotary motion from one gear to another.

Figure 3: Chain Drive

7. Throttle: The throttle is connected to the controller through wiring whose function is to regulate or control the speed of the motor.

Figure 4: Throttle

8. Battery charger: This charger takes the electric current from the main supply and is connected to a charger plug of a controller which supplies the flow of current to the battery. This wall charger can charge the pack of 4 batteries connected in series in 5-6 hours.

Figure 5: Wall Battery charger

6. Key switch: Key switch is the component which channels the power flow from battery to motor, when in the ON condition.

Figure 6: Key switch

7. E-Bike LCD Display: An LCD display was integrated to provide real-time information on speed, battery level, assist level, and distance traveled.

Figure 7: E-Bike LCD Display

8. Wiring: Waterproof connectors and wiring harnesses were used to ensure reliable and weather-resistant connections between all components.

9. Torque Arms: Steel torque arms were fabricated to reinforce the rear dropouts and prevent the motor axle from spinning under load.

10. Sensors:
Torque Sensor: A load-cell-based mini-sensor was integrated into the bottom bracket to measure the rider's pedal torque in real-time.
Speed Sensor: A Hall effect sensor was mounted on the rear wheel to measure its rotational speed (RPM).

11. User Interface: A handlebar-mounted display with buttons allowed the user to set the target speed and receive feedback on system status.

3.2 Theoretical Considerations

A pedal assist electric bicycle requires human power for the motor to disengage (Prebus, 2017). To determine the human power, a torque sensor and a cadence sensor were installed in the E-bike. Equation1 below gives the equation for calculating the human power, equation 2 gives the angular velocity and equation 3 gives the human output power.
In its simplest form, the equation for human power Phuman is expressed as the product of the pedal torque, and angular velocity

$$\text{Phuman} = \tau\text{pedal} \,.\, \omega\text{pedal} \qquad \text{(Eq.1)}$$

where:
$Phuman$ is the human power output in Watts (W).
$\tau pedal$ is the torque applied to the pedals, typically measured in Newton-meters (N•m).
$\omega pedal$ is the pedaling cadence or angular velocity in radians per second (rad/s).
Since cadence is often measured in revolutions per minute (RPM), the angular velocity can be calculated using the following conversion:

$$\omega pedal = \frac{(2\pi.\text{Candence (RPM)})}{60} \qquad \text{(Eq.2)}$$

Therefore, the human power equation can be written as:

$$\text{Phuman} = \tau\text{pedal}. \frac{(2\pi.\text{Candence (RPM)})}{60} \qquad \text{(Eq.3)}$$

3.3 Integration into the E-bike System

In a pedal-assist e-bike, the total power driving the bicycle is the sum of the human power, Phuman, and the motor power, P$motor$. This combined power must be sufficient to overcome various forces resisting the motion of the bicycle, such as rolling resistance, aerodynamic drag, and gravitational forces on an incline.

$$Ptotal = Phuman + Pmotor \qquad \text{(Eq.4)}$$

The adaptive speed control system developed in this research uses the measured human power ($Phuman$) as a key input to determine the required motor assistance ($Pmotor$). By continuously monitoring and calculating the rider's effort, the controller can modulate the motor's power output to maintain the target speed while creating a more natural and intuitive riding experience. The fuzzy-PI controller utilizes this information to dynamically adjust its gain parameters, providing a seamless blend of human and electric power. The testing and performance evaluation of the pedal-assisted e-bike were conducted through a series of systematic tests to ensure its functionality, safety, and reliability. Figure 1 shows the assembled E-bike used during testing.

Figure 8: Locally assembled E-bike

3.4 Fuzzy PI Controller for Adaptive E-Bike Speed Control

A Fuzzy-PI controller combines the advantages of fuzzy logic and traditional proportional-integral (PI) control to provide adaptive speed control for e-bikes. In this control scheme, fuzzy logic dynamically tunes the PI controller parameters based on real-time measurements of speed error and change in error, enabling the system to handle nonlinearities and uncertainties better than a conventional fixed-parameter PI controller. This approach improves the e-bike motor's speed response by offering faster rise and settling times, reducing overshoot, and maintaining stability under varying load and riding conditions. Implementation typically involves using a microcontroller.

Overall, a fuzzy-PI controller represents an effective, cost-efficient solution for intelligent speed control in pedal-assisted e-bikes, enabling responsive and adaptive motor assistance tailored to dynamic rider behavior and environmental conditions.

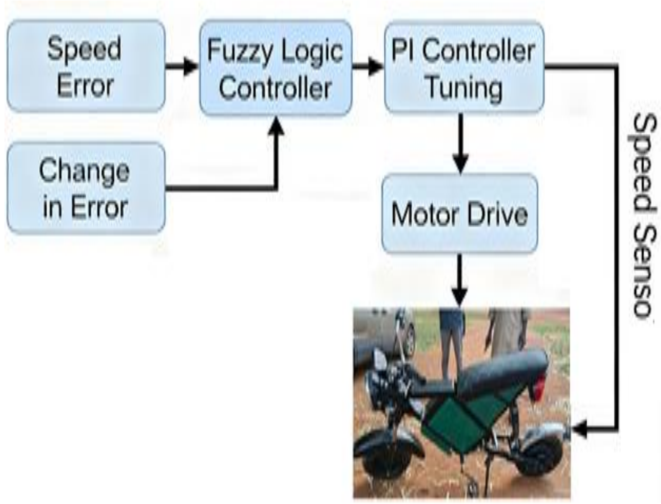

Figure 9: A block diagram of the fuzzy-PI e-bike control system

In a fuzzy-PI controller used for adaptive e-bike speed control, the fuzzy tuner typically uses two inputs:

1. Error (e) — difference between the desired speed and actual speed.
2. Change in error (Δe) — the rate of change of the error.

Membership Functions (MFs)

- Both error and change in error inputs are divided into fuzzy sets such as: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Large (PL)

Each fuzzy set has an associated membership function, often triangular or trapezoidal shaped, defined over the universe of discourse (range of values). The output of the fuzzy tuner, which adjusts the proportional (Kp) and integral (Ki) gains, also has similar fuzzy sets.

Rule Base

The fuzzy rule base consists of rules of the form:

- IF error is **NL** AND change in error is **NM** THEN Kp is **PL**, Ki is **PM**
- IF error is **Z** AND change in error is **Z** THEN Kp is **ZS** (zero small), Ki is **ZS**
- IF error is **PS** AND change in error is **NS** THEN Kp is **PM**, Ki is **PL**

Rules are designed to increase gains when the error is large and decrease them when the error approaches zero, ensuring smooth control.

4. Results and Discussion

The fabricated pedal-assisted e-bike was subjected to a series of tests to evaluate its performance metrics, including Speed Stability (Settling Time), Speed Overshoot, Energy Efficiency, Response to Load Variation, Rider Experience (Comfort), Ease of Use and Adaptability. The results are shown in Table 1 below.

The adaptive system automatically manages power delivery, allowing the rider to focus on steering and navigation rather than constantly adjusting settings. Adaptability High, self-tuning capability Low, fixed parameters The fuzzy logic component enables the controller to adjust its performance based on real-time conditions and driver input, offering a superior and more adaptable control.

Table 1: Comparative Performance Evaluation of Adaptive Fuzzy-PI vs. Conventional PI **Control**

Performance Metric	**Adaptive Fuzzy-PI Control System**	**Conventional PI Control System**	**Improvement & Implication**
Speed Stability (Settling Time)	Fast (~0.1 s recovery)	Slow (~0.3 s recovery)	3x faster response to disturbances like hills, providing a more stable and confident ride.
Speed Overshoot	Minimal (< 2% deviation)	Significant (> 7% deviation)	Smoother speed maintenance; eliminates jerky acceleration/deceleration, enhancing comfort and safety.
Energy Efficiency	High (Optimal power delivery)	Low (Often inefficient usage)	Extended battery life and range via dynamic power modulation that matches real-time load demands.
Response to Load Variation	Robust & Instantaneous	Lagging & Insufficient	Seamless adaptation to inclines and headwinds, maintaining target speed with minimal rider effort.
Rider Experience (Comfort)	Smooth & Intuitive	Jerky & Less Responsive	Natural cycling feel; motor assistance blends imperceptibly with human power, reducing fatigue.
Ease of Use	Automated, Hands-off	Manual, Requires Adjustment	Set-and-forget operation; rider focuses on steering, not constantly managing assist levels.
Adaptability	High (Self-tuning parameters)	Low (Fixed parameters)	Versatile performance across different riders, terrains, and conditions without manual recalibration.

4.1 Discussion of Comparative Performance

The comparative table effectively explain the superior performance of the adaptive fuzzy-PI control system across multiple key metrics when compared to a conventional, fixed-gain PI controller. Each metric underscores a distinct advantage, collectively demonstrating that the adaptive approach offers a more stable, efficient, and user-friendly experience for e-bike riders.

- **Speed Stability and Settling Time**

The comparison of speed stability and settling time reveals the most significant advantage of the adaptive controller. While a conventional PI system responds to load changes with a slower, more oscillatory reaction, the adaptive fuzzy-PI system uses dynamic gain tuning to react near-instantaneously. This improved stability is crucial for rider comfort and confidence, as it eliminates the need to constantly monitor and manually adjust settings to maintain a consistent speed.

- **Speed Overshoot**

The table indicates that the adaptive system minimizes speed overshoot and undershoot during load changes, whereas the conventional system produces more pronounced fluctuations. The reduction in speed oscillations contributes to a more refined and natural-feeling ride, which is a major factor in improving the overall rider experience.

- **Energy Efficiency**

The evaluation shows the adaptive controller is more energy-efficient, primarily due to its ability to modulate power delivery optimally for the current load. By avoiding excessive or unnecessary power output, the system extends battery life, especially in urban environments with frequent changes in terrain and rider input. This efficiency gain provides riders with a longer range and reduces the frequency of charging.

- **Response to Load Variation and Rider Experience**

The adaptive system's responsiveness to load variation translates directly to a superior rider experience. This high level of adaptability makes the ride more enjoyable and less fatiguing, particularly for extended commutes or varied terrain. In contrast, a conventional system requires the rider to manually manage assist levels, adding a layer of complexity and physical burden.

- **Ease of Use and Adaptability**

Ultimately, the adaptive system enhances the overall ease of use by automating power delivery. The rider can set their desired speed and focus on the road, with the system intelligently managing the power output in the background. The fuzzy logic component's self-tuning capability ensures the system can adapt to different riders and changing conditions, making it more versatile and robust than a controller with fixed parameters.

5. Conclusion

This research successfully developed and evaluated an adaptive speed control system for pedal-assisted electric bicycles (e-bikes), designed to enhance rider comfort, safety, and energy efficiency. Unlike conventional control strategies that rely on fixed gain parameters and provide static assistance levels, the proposed system integrates fuzzy-PI adaptive control with real-time sensor feedback to achieve intelligent and dynamic power modulation. The performance evaluation demonstrated significant improvements across operational metrics, including reduced settling time, minimized overshoot, enhanced responsiveness to load variations, and higher energy efficiency. Overall, the adaptive speed control system proves to be a highly effective solution for smart mobility applications, offering increased reliability and longer battery life while improving sustainability in personal transportation. The outcomes of this study show that intelligent control algorithms can greatly advance e-bike technology and support the growing demand for efficient and user-centric urban mobility devices.

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