Pedal Assist Torque Performance of Electric Bikes Driven by BLDC Motors on Uphill Roads

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***Abstract*—Riding bicycles as a means of transportation and recreation is becoming increasingly popular because bicycles are environmentally friendly and trendy for young people. However, behind its advantages and appeal, the bicycle gives problems when passing through an uphill road to the rider. It takes a lot of effort and energy to pedal and keep it moving. This research proposed a novelty method to solve uphill cycling by deploying the Fuzzy control system. A Mamdani type is selected to solve the assisted power calculation with torque, speed, and the angle of slope of the road as parameters. To make the system run in real-time, the microcontroller ATMega 2560 is used to record, process, and control the data. The research results show that bicycles without assisted power need an average of 8 times greater than the power-assisted bicycles on a slope of less than 15º. The maximum pedal torque needed is 1.5 times greater than the power-assisted bicycle, which is 80 Nm compared to 53 Nm. On the uphill road, the speed of a bicycle with assisted power is 4.4 times greater than the bicycle without assisted power. The average electric power consumption on assisted-power bicycles is 2.75 Wh/km, showing that the performance of bicycles with assisted power has many advantages compared to bicycles without assisted power.**

Keywords*— *assisted power, fuzzy logic, BLDC motor, microcontroller, bicycle

I. Introduction

The issue of global warming and environmental pollution by fuel oil is a hot topic of conversation today [1]. Dependence on petroleum makes its reserves dwindle [2]. The solution is to develop the electrification of transportation in electric vehicles [3-5]. Many researchers have conducted research to improve the efficiency and performance of electric motors [6] [7]. One of the electric motors that are widely used in the field of transportation is the Brushless Direct Current (BLDC) Motor [8-10]. Bicycles attached to electric motors are environmentally friendly transportation [11]. A group of people uses electric bikes for recreation and exercise. It is predicted that the market share of electric bicycles will increase along with the innovation of new models in the future [12].

Many researchers are motivated to conduct research related to the comfort and safety performance of electric bicycles. Researchers [13] place gyroscopic sensors to get stability and balance while cycling. While researchers [8], [10] have researched the desired torque setting to keep the motor torque constant. The method is to control the electromagnetic torque of the motor and observe changes in current. Another method for increasing the performance of electric bicycles is assisted power. Assisted power is power or torque assistance from a motor that is attached to a pedaling bike. The torque sensor is installed on the pedal as a detector to control the electric motor [14]. Besides that, assisted-power techniques on electric bicycles can also be carried out using a gear-shifting mechanism using fuzzy logic control [15-17]. To detect the angle of the road slope, Researcher [18] used an accelerometer sensor, and to estimate the motor torque, the researcher used a speed sensor and an electric current sensor.

Researchers [19] [20] conducted research and tested dynamic parameters and electricity consumption on electric bicycles. The method is based on the mass of the bike, the angle of inclination, and the radius of the wheel. The results of his research state that there is a relationship between the amount of electricity consumed which is influenced by wind resistance and the angle of the road slope. The tilt angle also influences the relationship between speed and electricity consumption. The speed will decrease when the slope angle increases and electricity consumption will also increase [19]. Most of the research that has been done is on the need for electricity consumption for conditions on flat roads, uphill roads, and downhill roads [18] [19]. In general, this research relates the need for electrical energy consumption from batteries to the three road conditions. Research on uphill road conditions [18] [19] has been carried out, but only to analyze electricity demand, while the analysis of the relationship between the performance of electric bicycles on uphill roads and electricity demand is debatable depending on the condition of the road angle and the load being carried.

Based on the literature review, it is proposed to study assisted-power electric bicycles with pedal assist using fuzzy control as a BLDC motor speed controller. This research uses a gyroscope sensor to obtain pedal assist torque performance information on an uphill road and electricity consumption information. To measure the performance of the pedal on an uphill road, fuzzy logic controls are used. The purpose of this research is to analyze and study the performance of the torque and speed relationship on an uphill road. The research results will be used to design assisted-power BLDC motors on uphill roads at constant speed in future studies. The fuzzy logic control design uses an Arduino microcontroller to control assisted power on BLDC motors. It is expected that this research can be applied to ordinary bicycles, especially bicycle hobbyists.

II. Methodology

This study uses a pedal bike paired with a conversion kit. A fuzzy control design is used to control BLDC motor rotation. Arduino IDE software is used to design fuzzy logic control algorithms on Arduino, and Matlab is used for data validation of fuzzy algorithms on Arduino.

A. Equation of Bicycle Dynamics on an Incline

Referring to the researcher [18], an explanation of the mechanism of the force that occurs when an electric bicycle is on an incline is shown in Fig. 1. The acceleration of the bicycle is influenced by several forces, namely the pedaling force of the bicycle and the moving force originating from the motorbike and road friction. In addition, the magnitude of the angle of inclination also affects the magnitude of the resulting acceleration. A more detailed explanation is stated in (1).

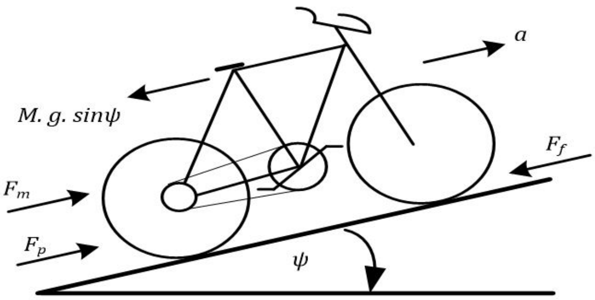


Fig. 1. Motion System on a Bicycle with Pedal Assist [18]

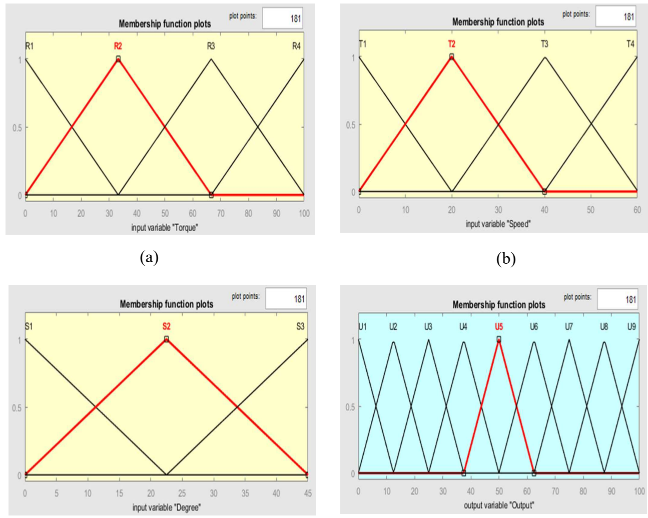
$$M.a = F_p - F_f - M.g.sin\psi + F_m \tag{1}$$

The total mass between the bike and the rider is denoted by M. While g, a, and ψ denote the gravitational acceleration, longitudinal acceleration, and slope of the road, respectively. The force generated by the cyclist is expressed by F_p while the force generated by the motor is expressed by F_m. The friction is represented by F_f. The compensating factor that affects the motion of the system is referred to as the assist ratio. The compensation value may not exceed the weight of the bicycle (M) or be expressed as $0 > \eta \geq \frac{M_g}{M}$.

B. Fuzzy Logic Control Design

Fuzzy logic control is used to generate control signals for the motor driver. Fuzzy membership function (MF) design using the Simulink/Matlab environment. The type of fuzzy control used is the Mamdani fuzzy, with three inputs and one output. The three fuzzy inputs are pedaling torque, speed, and road contour angle. Each of the three fuzzy inputs has a different number of membership functions. The pedaling torque input has a membership function of 4, consisting of no pedaling (R1), light stroke (R2), medium stroke (R3), and heavy stroke (R4). Speed input has a number of membership functions of 4, including stop (T1), slow speed (T2), medium speed (T3), and high speed (T4) conditions. Meanwhile, the input angle of the road has three membership functions, namely downhill road conditions (S1), flat road conditions (S2), and uphill road conditions (S3). While the membership function for output consists of nine variables, including U1, U2, U3, U4, U5, U6, U7, U8, and U9. The complete design for the fuzzy membership function is shown in Fig. 2.

The operating range (OR) or torque range is set at (0 – 100) Nm. While the OR for speed is set between (0 – 60) km/h. While the OR for corner conditions is set from (0 – 45)°. The OR output is set in percentage, which is between (0 – 100)%. The MF shape is chosen to be triangular with 50% overlapping the other. OR and MF details are shown in Fig. 2.



(a) (b) (c) (d)

Fig. 2. Fuzzy membership function for each input and output

For fuzzy output, use the "IF-THEN" fuzzy rules with the "AND" operator. Fired fuzzy rules are described in Table I.

TABLE I FIRED RULE FUZZY

	R1	R2	R3	R4	S
T1	U1	U2	U3	U4	S1
T2	U2	U3	U4	U5	
T3	U3	U4	U5	U6	
T4	U4	U5	U6	U7	

	R1	R2	R3	R4	S
T1	U2	U3	U4	U5	S2
T2	U3	U4	U5	U6	
T3	U4	U5	U6	U7	
T4	U5	U6	U7	U8	

	R1	R2	R3	R4	S
T1	U3	U4	U5	U6	S3
T2	U4	U5	U6	U7	
T3	U5	U6	U7	U8	
T4	U6	U7	U8	U9	

C. Block Diagram of the Pedal Assist Control System

BLDC motor speed control is obtained from the driver module, which generates a 3-phase trapezium signal. The driver input is obtained from the fuzzy control output, which processes three inputs, namely torque, speed, and road contour angle. 'Torque input' is the sum of the torque of the cyclist and the torque of the BLDC motor. A pitch sensor detects the slope of the road. This system uses the sensor type of BLDC, which has hall sensors to detect magnetic polarity. The output from FLC is used to drive BLCD via a universal BLCD driver and creates a bike motion system. The block diagram details are shown in Fig. 3.

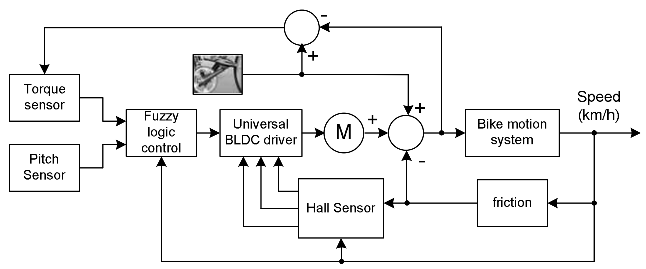


Fig. 3. System block diagram

The Fuzzy Logic Algorithm from MATLAB is adopted into the Arduino program, which is connected to the electric bicycle motor driver. The driver module uses the Universal BLDC Controller and is installed on an ordinary (manual) bicycle.

The overall design of the module and control components for an electric bicycle with a BLDC motor is shown in Fig. 4. The algorithm and programming of the MATLAB simulation results are stored in the Arduino Uno microcontroller to be executed in the conversion kit module installed on the bicycle.

Fig. 4. Overall System Design

Table II shows the name of the module used to design this study's control system. The design of an electric bicycle is modified from an ordinary bicycle, equipped with a Conversion Kit installed on the bicycle frame, wheels, and pedal shaft. Type of 500W 3-phase BLDC Rear Hub motor as the driver. 800W universal driver power, for a 3-phase signal output regulation. This driving motor is powered by a 18650-48V lithium-ion battery pack with a capacity of 10.4 Ah.

TABLE II ELECTRIC BIKE MODEL MODULES AND MATERIALS

Module/Material Name	Type
Electric bike conversion Kit	- Rear hub BLDC 500W 120° 3 Phase - Universal BLDC controller 800W - Battery Li-ion pack 48V 10.4 Ah - Brake switch
Main controller	Arduino Mega 2560
Shield board	Arduino Mega Screw Shield
Display module	LCD 4x20 char + I2C driver
Gyroscope module	MPU6050
DAC module	MCP4725
Pedal torque sensor	T13 68
12V power supply	DC to DC converter 60 to 12V
5V power supply	DC to DC converter 60 to 5V

III. RESULTS AND DISCUSSION

Before carrying out data collection, observations were made to test the performance of electric bicycles without pedal assist. The data was taken using the algorithm on Arduino after being simulated in MATLAB first. The sampling time is 200 ms, and the total data collection time was 30 seconds; the cyclist's weight is 53 kg.

The test was carried out on an uphill road with a slope angle of <15° with consideration for cyclists' balance and safety. The test was divided into two types, namely pedaling conditions without assisted-power assistance and with assisted-power assistance.

Measurement of a pedaling bicycle on an uphill road without assisted power shows that the intensity of the number of strokes is quite frequent if you want to maintain speed (Fig. 5(a)). In Fig. 5(a), it can be seen that the cyclist is trying to pedal to produce a large enough pedaling torque. The cyclist's maximum pedaling torque on this uphill road condition reaches 80 Nm. Meanwhile, Fig. 5(b) shows the changing street corner conditions with a maximum slope angle of less than 15°. On the other hand, the amount of pedaling torque from the cyclist cannot produce a stable speed or provide a sense of comfort to maintain the cyclist's balance. The resulting maximum speed is only 4 km/h as shown in Fig. 5(c).

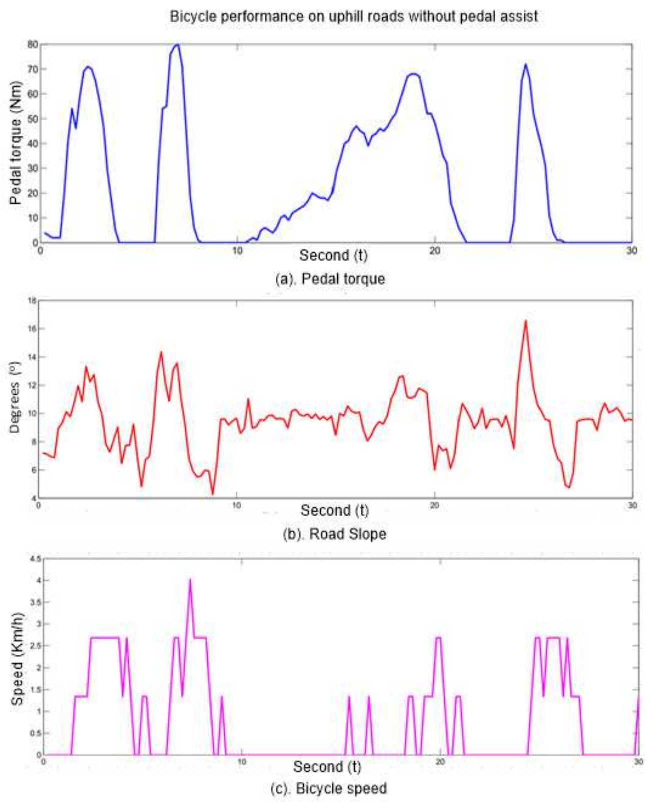


Fig. 5. Bicycle performance on an uphill road without assisted power.

On the other hand, in testing bicycles on the uphill road using assisted power, the frequency of the number of strokes has decreased (Fig. 6(a)). The magnitude of the cyclist's pedaling torque that must be issued is 53 Nm at the peak and continues to decrease as the speed is maintained, and then the speed drops to zero. The maximum speed achieved is 18.77 km/h, as shown in Fig. 6(b) and 6(c).

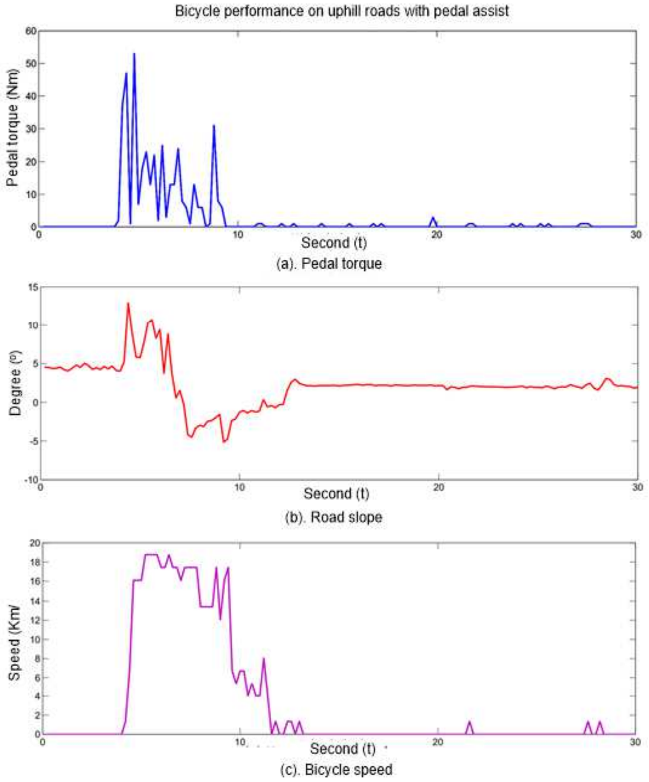


Fig. 6. Bicycle performance on an uphill road with assisted power.

Fig. 7(a) shows the value of the control signal that must be issued to provide a generation signal to the BLDC motor. The most significant value of the controller signal is close to 70% when the incline angle of the road is around 14º. Consequently, the maximum power consumption requirement is when the incline angle of the road is 14º, which is 1200 W, as shown in Fig. 7(b). Due to the uphill road corner contour, the motorcycle must keep going and fight against the drag force. The average power consumption at the controller output is 12.86%, but the average power consumption for the motor is 58.07 W.

Table III shows the average performance measurement of a bicycle on the uphill road without assisted power and with assisted power. Based on the data in Table III, without assisted power from the BLDC motorbike, the average torque that must be expended is 8 times more than that of an assisted-power bicycle. The average speed at the same road contour angle shows that an assisted-power bicycle is 4.4 times faster. This is because of the additional boost provided by the BLDC motor. Even though assisted-power bikes have advantages in terms of lighter pedaling torque and extra speed, there is a consequence of the need for an electric power source that must be provided. The microcontroller's electric power consumption is 12.86% and the electric power consumption for BLDC motors is 58.07 W.

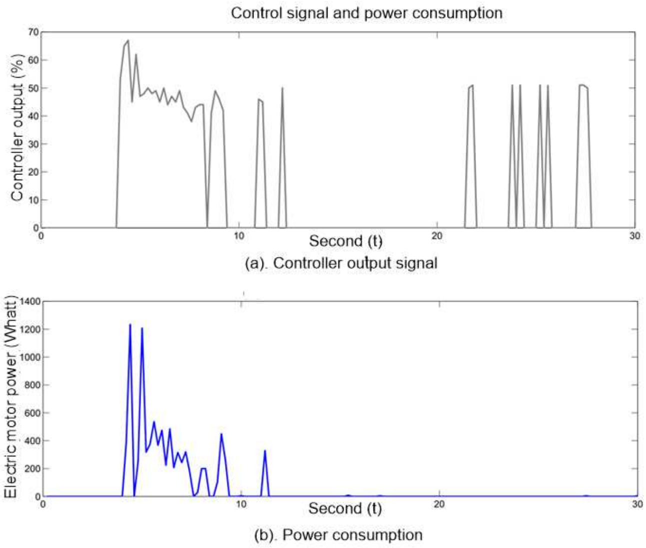


Fig. 7. The control signal and power consumption for power-assisted

TABLE III COMPARISON OF THE AVERAGE PERFORMANCE MEASUREMENT OF A BICYCLE ON AN INCLINE

	Without assisted power	With assisted power
Average pedaling torque (N.m)	21.973	2.727
Road Contour Angle (º)	9.4088	9.216
Average speed (km/h)	0.732	3.244
Average speed (km/h)	0	12.28
Average controller output (%)	0	58.07

IV. CONCLUSION

Based on our experiment, the proposed method is successfully applied on uphill road conditions with a slope angle of less than 15º, bicycles without assisted power require an average pedaling torque 8 times greater than bicycles with assisted power. At the same time, the maximum pedaling torque on an assisted-power bike is 80 Nm with a top speed of 4 km/h. Meanwhile, assisted-power bicycles have a maximum torque of 53 Nm at a full speed of 18.77 km/h, while the average speed produces 4.4 times more torque. Thus, the steeper the angle of the road, the greater the pedaling force that must be applied. Triggers the motor to assist in thrust, easing the cyclists' pedaling. The total average electric power consumption for electric motor torque generation, speed, and angle of the road is 2.75Wh/km.

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