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Adaptive Speed and Power Control for a Pedelec Using an ARM Cortex-M0 Microcontroller

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Abstract: The paper presents a study which aimed to implement adaptive speed and power control for a pedal-assisted electric bicycle using Infineon's 32-bit ARM Cortex-M0 microcontroller. The adaptive speed and power control were achieved by using proportional-integral closed-loop feedback control. The study covered the equations for computing human power, theoretical power, and the proportional-integral equations used for targeting power and targeting speed. The data obtained proved that the electric bicycle achieved and maintained the target speed manually set the by user, with a percentage error of less than 10%, all the while being relatively as efficient as a commercial-grade motor controller. Furthermore, three different modes for pedal-assist's target power were implemented, namely Executive, Mid, and Sports. The data obtained for pedal-assist showed that the percentage error in target power is all below 10% which signifies that the system can reach its target power. The research opens the possibilities of improving the existing adaptive speed and power control as well as the possibilities of improving the mobile application of the e-bike which interfaces with the user.

Key Words: Electric bicycle; BLDC motor control; PID; Pedal Assist; Infineon

1. INTRODUCTION

1.1 Background of the Study

Biking is a healthy, and eco-friendly mode of transportation (Clain, 2017). Biking daily is tiresome for new bikers who are not used to biking long distances. The solution is an electric bicycle – a pedal-assisted bicycle which helps the biker accelerate the e-bike. However, before the electric bicycle may assist the biker, it must have an algorithm that will properly stimulate the brushless DC motor. There are several algorithms in controlling the motor which will be discussed in the related literatures. Due to the requirement of an algorithm, the study integrated a microcontroller with the electric bicycle to perform advanced motor control algorithms.

Effective motor control should reach its quantitative target values, such as speed, power, or torque while maintaining an efficient power consumption of the battery. On the other hand, the motor control algorithm should make the user experience feel smooth and comfortable. Ultimately, the motor control algorithm should neither be too aggressive in meeting its target values, or be too sluggish in driving the motor.

1.2 Review of Related Literature

The first study wanted to estimate the parameters of speed control of a permanent magnet DC motor (PMDC) used in a wheelchair through MATLAB/Simulink simulations (Sankardoss & Geethanjali, 2017). This research enumerated three control algorithms for the control of the wheelchair, specifically Proportional-Integral (PI), Proportional-Integral-Derivative (PID) and a state feedback speed controller. Their research has concluded that out of the three controllers, the state feedback controller produced the lowest peak overshoots and the fastest settling times. On the other hand, PI and PID control are the more practical alternatives since it achieves the goal at a fraction of the computational cost. Based on the related literature, the proponents decided to prioritize computational efficiency over a perfect response due to two reasons. First reason, the 32-bit microcontroller used in the research is weak in terms of processing capability, especially when compared to a desktop computer. The second reason is because minimizing the overshoot or the settling time is not crucial in the electric bicycle, in fact, considering these factors may place unnecessary strain on the microcontroller. The research maintains its novelty because a three-phase BLDC motor is controlled, thus there are a total of 6 different PWM signals applied to the motor simultaneously.

Another study, regarding the techniques for efficiency improvement in PWM motor drives discussed areas where power is lost when driving a motor by pulse-width generated signals (Di Piazza & Pucci, 2016). Their paper suggested that the power loss comes from the converter and the induction motor. These two factors are important when considering the overall efficiency of the system. One of the solutions mentioned in the paper was by modifying the pulse width modulation technique. The researcher's suggestion was taken into consideration as there were three different methods to drive the motor used in this research, namely low-side PWM control, high-side PWM control, and synchronous PWM control.

1.3 Objectives

The study aimed to develop an adaptive speed and power motor control algorithm for a pedal-assisted e-bike using the Infineon's XMC1302, a 32-bit ARM-Cortex-M0 microcontroller. The adaptive speed method would target a specific speed regardless of the total weight, road conditions, and losses of the system. The adaptive power method on the other hand would target a specified ratio of power between the e-bike and the user under the same scenario. The researchers named the three ratios Executive, Mid, and Sports. Specifically, the researchers aim to achieve less than a 10% error in controlling both the target speed and target power of the electric bicycle. Finally, the research aimed to achieve an efficiency of at least 60% when controlling the BLDC motor which would be achieved by trying the different PWM control methods.

1.4 Scopes and Delimitations

The study is limited by the hardware designed by the researchers for motor control. A motor controller bought from the market is incapable of performing advanced algorithms so the best choice it a customized motor controller (Mallari, Macaraig, Navarrete & Marfori, 2016). Furthermore, the study only dived in the algorithm for achieving the target speed and target power independently. The study analyzed in detail the data obtained from the electric bicycle via telemetry and assumed that the system can store data for future analysis. The study only used the PI control method in the research as it is practical in terms of computational extensiveness and actual performance for the case of a 32-bit microcontroller. The study only used sensors that can measure speed, throttle input, voltage, current, power and cadence and torque. Additionally, the research is confined to the limits of the motor of the electric bicycle. The motor used in the research is a 350W rated BLDC motor operating at 36V with a top-speed of 35kph during freewheel.

2. METHODOLOGY

The methodology is composed of three different sections, namely the theoretical considerations, torque sensor calibration, as well as the software design and considerations. The theoretical considerations explain how pedal-assist is a combination of the human and motor power and how the theoretical power is computed using bicycle kinematics formulas. Furthermore, the torque sensor calibration covers the steps taken to accurately calibrate the torque sensor installed on the electric bicycle.

2.1 Theoretical Considerations

2.1.1 Pedal-Assist with Human and Motor Power

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. Equation 1 below gives the equation for calculating the human power.

$$P_h = \tau * (2\pi * \omega) \quad \text{(Eq.1)}$$

where:

P_h = Human power (W)
τ = Torque (Nm)
ω = Cadence (rps)

Equation 2 on the other hand is the computation for torque.

$$\tau = F * \frac{r}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos(x)\, dx \quad \text{(Eq. 2)}$$

where:

τ = Torque (Nm)
F = Human force (N)
r = Crank radius (m)

Three modes were implemented for pedal-assist namely, Executive, Mid and Sports. The researchers defined each mode with respect to the ratio between the power delivered by the motor to the power exerted by the human. Executive mode was designed to get 70% of the power from the motor with the remaining 30% of the power from the human. Mid mode was specified to have an equal, 50%-50% share between the motor and the human. Finally, Sports mode was conceptualized to allow the motor to exert only 30% of the power while the human generates 70% of the power. Table 1 summarizes power exerted by both the motor and the human in terms of percentage.

Table 1. Power Ratios (%) between Human and Motor

Mode	Motor Power (%)	Human Power (%)
Executive	70%	30%
Mid	50%	50%
Sports	30%	70%

2.1.2 Vehicle Kinematics Formula and Theoretical Power Computation

Power is needed to move the electric bicycle at any given speed. Equation 3 shows the factors that affect the required power to move the electric bicycle [3]. The human and the motor combined must exert more power when riding uphill, in rough roads, and in windy places.

$$P_{theo} = \frac{P_{drag} + P_{fric} + P_{hill}}{E_{ff}} \quad \text{(Eq. 3)}$$

where:

P_{theo} = Theoretical power of bike (W)
P_{drag} = Power to overcome air drag (W)
P_{fric} = Power to overcome rolling resistance (W)
P_{hill} = Power to overcome slopes (W)
E_{ff} = E-bike efficiency; $0 \leq E_{ff} \leq 1$

Equation 3 can be expanded to consider the characteristics of the e-bike and the rider resulting to Equation 4.

$$P_{theo} = \frac{\frac{1}{2}(\rho A V^2 C_D)V + [(m_B + m_R) g C_R]V + (m_B + m_R) g (V \sin\theta)}{E_{ff}} \quad \text{(Eq. 4)}$$

where:

V = Velocity (m/s)
m_b = Mass of bicycle (kg)
m_r = Mass of rider (kg)
g = Acceleration due to gravity; $9.8 m/s^2$
C_{RR} = Coefficient of rolling resistance
ρ = Air density; $1.2 kg/m^3$
A = Bicycle + rider's frontal area in m^2
C_D = Coefficient of drag
θ = Inclination angle (pitch) in degrees
E_{ff} = E-bike efficiency; $0 \leq E_{ff} \leq 1$

2.2 Torque Sensor Calibration

The procedure for calibrating the torque sensor required multiple metal plates that were weighed on a weighing scale. The procedure also required an instrument to check the angle of elevation to ensure that $\cos\theta$ would equate to one. The crank of the electric bicycle was set to be parallel to the ground and weights were placed on the crank's farthest point, which was considered as the radius of the crank. The applied weights caused the torque sensor to have a delta in its current voltage, which is then read and converted by the microcontroller into a digital signal. Because a theoretical torque may be calculated using the torque equation, the torque read by the microcontroller may be calibrated with respect to the actual torque. The procedure was repeated until 30lbs were stacked on the brank. Figure 1 shows the set up for torque calibration.

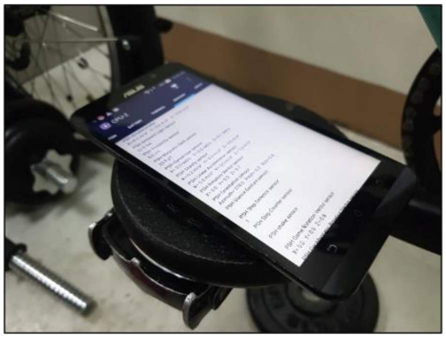

Fig. 1. Metal plate (~2.5lbs) on the Crank

2.3 Software Design and Considerations

2.3.1 Determination of Bicycle Kinematics Constants

The constants used for Equation 4 can be assumed using the research from Scientific American. In their paper, there's a list for how different factors affect constants for drag coefficient, frontal area, and rolling resistance among others (Gross, Kyle & Malewicki, 1983). Table 2 shows how different positions in riding the bicycle affect the overall performance of the system.

Table 2. Performance of Various Biking Positions

Description	Drag Coefficient	Frontal Area (ft^2)	Rolling Resistance
Off-road Racer	1.10	4.9	0.0140
Upright Commuter	1.10	5.5	0.0060
Arms Straight	1.00	4.3	0.0045
Fully Crouched	0.88	3.9	0.0030

2.3.2 Speed Control using Classical PI Control

The computation for target speed is the product of $Throttle_{val}$ and V_{max}. There is a throttle sensor integrated onto the electric bicycle. It was calibrated to have values ranging from zero (0.0) to one (1.0) which represented the throttle level. The electric bicycle's software had a constant declared that specifies the top speed which was set to 35 kph. The formula is found in equation 5:

$$V_{target} = Throttle_{val} * V_{max} \quad \text{(Eq. 5)}$$

where:

V_{target} = Target velocity (kph)
$Throttle_{val}$ = Value: $0 \leq Throttle_{val} \leq 1$
V_{max} = Maximum velocity (kph)

The e-bike's target speed was obtained using PI control algorithms. The PWM duty cycle adjusted every 250ms. The relationship between the PWM duty cycle with the speed is directly proportional as long as the road condition and the mass of system remains unchanged. The formula for computing the new PWM value is in equation 6:

$$PWM_{new} = PWM_{old} + \left(K_p * error_p + K_i * error_i\right) \quad \text{(Eq. 6)}$$

where:

PWM_{new} = New PWM Duty Cycle
PWM_{old} = Old PWM Duty Cycle
K_p = Proportional constant; $4.0*10^{-3}$
$error_p$ = Difference between Target Speed and Current Speed
K_i = Integral constant; $0.4375*10^{-3}$
$error_i$ = Integral of $error_p/4$ for the previous 4 readings

Because the motor exerts all the power in speed control, it is important for the motor to maintain a smooth response especially when accelerating. Applying a 90% duty cycle when the e-bike is at rest introduces two problems. First, such a high duty cycle gives the system an acceleration that is not comfortable for the user. Second, a high duty cycle applied at low speeds is inefficient for the motor and it also caused the battery management system to force the motor off due to an extremely high current draw. In order to solve the issue, a PWM_{limit} was introduced which sets the maximum duty cycle that may be used on a certain speed, its formula is as follows:

$$PWM_{limit} = 0.35 + 0.65\left(\frac{V_{current}}{V_{max}}\right) \quad \text{(Eq. 7)}$$

where:

PWM_{limit} = Maximum PWM Duty Cycle
$V_{current}$ = Current velocity (kph)
V_{max} = Proportional constant

The flowchart for speed control is found in Figure 2:

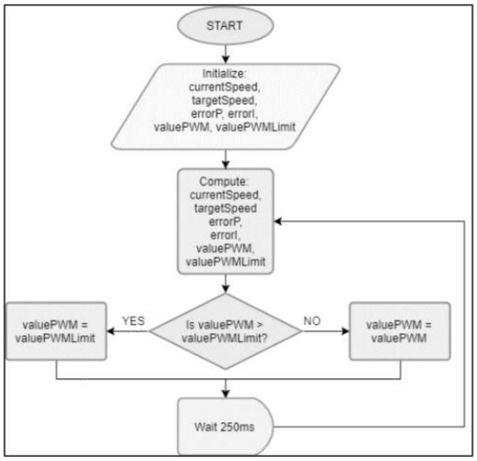

Fig. 2. Speed Control Flowchart

2.3.3 Power Control using Classical PI Control

The computation for target power followed a similar pattern to the computation for target speed. For the value to be computed, two sensors are integrated onto the electric bicycle. One is a cadence sensor, which detects how fast the rider pedals in rpm, while the other is a torque sensor which detects how heavy or how light the rider is pedaling. Furthermore, the 'mode' of the electric bicycle is considered. The paper considered three operational modes of the e-bike, namely "Executive", "Mid" and "Sports". In executive mode, the power ratio is 2.333, in mid mode, the power ratio is 1.0 and in Sports mode the power ratio is 0.429. The formula for target power is as follows:

$$P_{target} = \omega_{rpm} * \tau * p_r \qquad \text{(Eq. 8)}$$

where:

P_{target}	=	Target power (W)
ω_{rpm}	=	Cadence (rpm)
τ	=	Torque (Nm)
p_r	=	Power ratio (depends on mode)

Moreover, the target power was obtained by also using PI control algorithms. The PWM value also adjusts every 250ms and the formula used is found below:

$$PWM_{new} = PWM_{old} + \left(K_p * error_p + K_i * error_i\right) \qquad \text{(Eq. 9)}$$

where:

PWM_{new}	=	New PWM Duty Cycle
PWM_{old}	=	Old PWM Duty Cycle
K_p	=	Proportional constant; $0.5*10^{-3}$
$error_p$	=	Difference between Target Speed and Current Speed
K_i	=	Integral constant; $0.25*10^{-3}$
$error_i$	=	Integral of $error_p/4$ for the previous 4 readings

The flowchart for power control does not need a PWM Limit because the power of the motor depends on the power exerted by the human. The motor doesn't drive the system, but instead assists the biker in driving the system. Thus, if the user were to pedal in a way that causes high acceleration, the motor would act as a boost to the users pedaling. The flowchart for power control is found in the Figure 3.

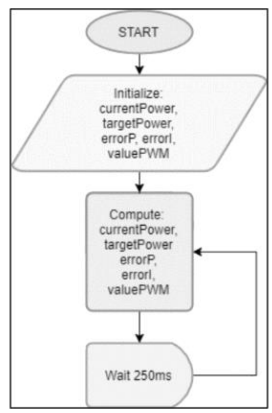

Fig. 3. Power Control Flowchart

3. RESULTS AND DISCUSSION

3.1 Calibration of Torque Sensor

It is important to calibrate the torque sensor before proceeding with the rest of the tests. Without calibrating the torque sensor, the human power computed by the microcontroller would be too erroneous to ensure that the power control PI algorithm will follow the specified power ratios. After the procedure under section 2.2 was followed, data for calibrating the torque sensor for the microcontroller was obtained in Table 3. The calculated trendline of plotting Torque vs. delta bits equated to $y = (0.1154*10^{-3})x^2 + (40.06*10^{-3})x$ with an R^2 value of 0.9997 which signifies that the line of best fit accurately describes the output of the sensor. The radius for each measurement is 16.4cm.

Table 3. Torque Sensor Calibration

Weight(lb)	T (N*m)	V (read)	V (actual)	%Error
0.0	0.0	2.945	2.963	0.6056
2.8	2.0	2.995	3.006	0.3621
5.2	3.8	3.040	3.051	0.3509
7.8	5.7	3.078	3.089	0.3514
10.2	7.4	3.112	3.123	0.3416
12.8	9.3	3.138	3.150	0.3818
15.2	11.1	3.167	3.177	0.3060
17.6	12.8	3.193	3.204	0.3459
20.0	14.6	3.214	3.225	0.3512
22.4	16.3	3.239	3.250	0.3287
25.0	18.2	3.263	3.272	0.2899
27.5	20.1	3.286	3.295	0.2818
30.0	21.9	3.305	3.317	0.3542

3.2 Target Speed vs. Actual Speed

Achieving the target speed requires an algorithm that used PI control to control the actual speed of the electric bicycle. Data gathered had the user select the target speed between 14kph and 25kph. The data in Figure 4 does not include the initial acceleration of the electric bicycle because setting a target speed of 25kph when the e-bike is at rest would take time until the e-bike accelerates to that point. The data in Figure 4 was gathered around a relatively flat rotunda outside De La Salle University – Laguna Campus and it plots the target speed with the actual speed. The total weight of the system is 79kg.

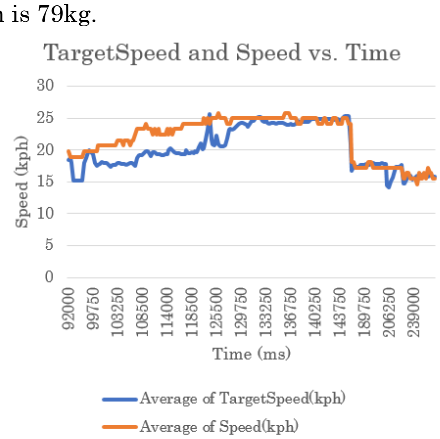

Fig. 4. Target Speed vs. Actual Speed

The results gave an average percentage error of 9.62% which is in line with the objective of having less than 10% error on the target speed. The graph signified that the PI algorithm is effective in modifying the PWM duty cycle to reach the desired target speed set by the user. However, error still existed because the road has slight variations in inclination which introduces error in the graph, especially when the e-bike is slightly going downhill. Nevertheless, the actual speed is greater than the target speed in most cases which proves that the e-bike can reach the desired speed.

3.3 Human Power, Target Motor Power and Actual Motor Power vs. Time

Achieving the target motor power used an algorithm which detects the human's input power and computes for the required motor power to meet the required ratio of humanPower:motorPower. The human's input power is determined by the calibrated torque sensor along with the cadence sensor. The motor power data is the product of the battery's current and voltage, which was obtained from telemetry which came from the existing hardware and software features of the electric bicycle. Data was obtained by riding the e-bike with a total weight of 79kg. Figures 5, 6, and 7 plots the human power, target power, and actual power obtained in "Sports", "Mid", and "Executive" mode, respectively.

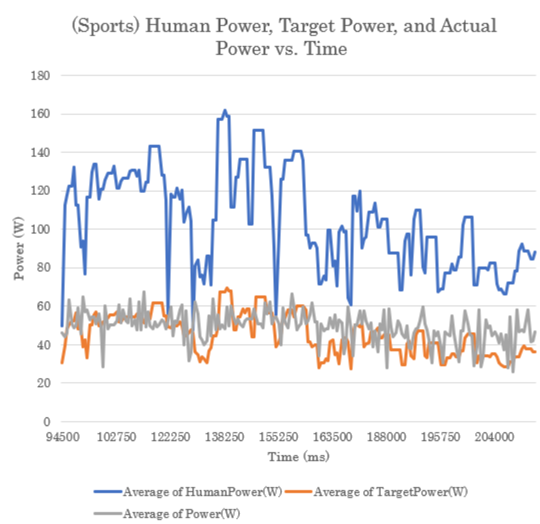

Fig. 5 Human Power, Target Power, and Actual Power vs. Time (Sports)

In sports mode, the human exerted 70% of the power while the motor exerted 30%. The data gathered was observed to have an average percentage error of 9.08% between the Target Power and the Actual Power.

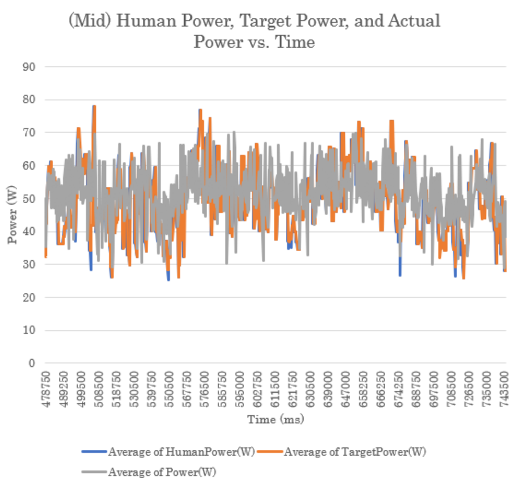

Fig. 6 Human Power, Target Power, and Actual Power vs. Time (Mid)

In Mid mode, the human and the motor both exerted 50% of the power as specified in the earlier sections. The data obtained was observed to have an average percentage error of 4.14% between the target power and the actual motor power.

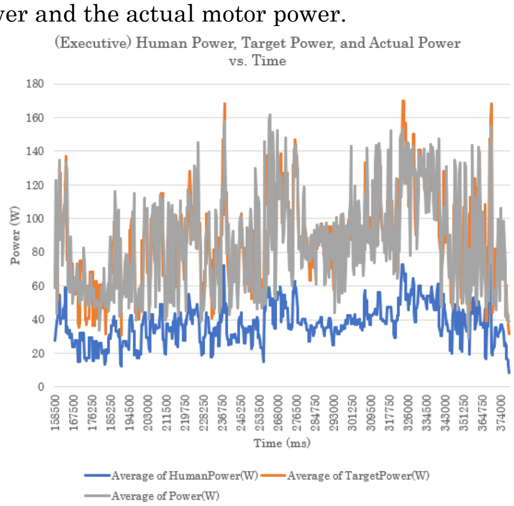

Fig. 7 Human Power, Target Power, and Actual Power vs. Time (Executive)

In Executive mode, the human exerted 30% of the power while the motor exerted 70% of the power. The data was analyzed to have an average percentage error of 2.54%.

It has been observed that the percentage error of reaching the target power decreases when the motor's power ratio with respect to the human increases (9.08% on Sports; 4.14% on Mid; 2.54% on Executive) because of how responsive the motor should be with changing cadence and torque readings. The reason why PI control was used was to decrease the response time at the cost of the presence of overshoot.

3.3 Total Power and Theoretical Power vs. Time

The data obtained in the figure below was from the same data set used in Figure 4. The motor power is the power exerted by motor, without any human power input. The data set is purely motor power which helped determine the actual efficiency of the electric bicycle. The theoretical power was computed using Equation 4. Figure 8 plots the measured to total power along with the calculated theoretical power in order to derive the efficiency of the system.

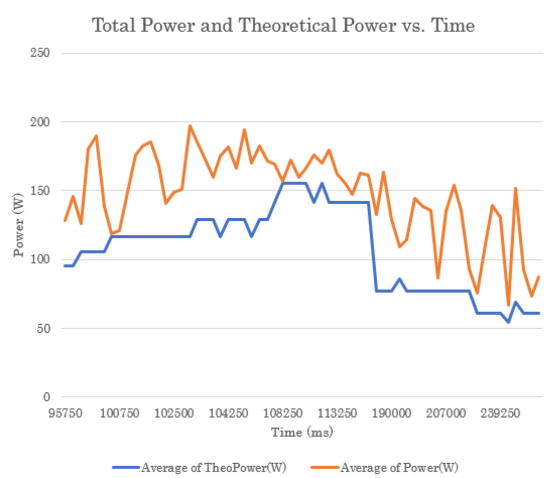

Fig. 8 Total Power and Theoretical Power vs. Time

The data shows the graph between the theoretical power (blue line), or the power theoretically needed to run the bike with respect to the actual power used by the bike (orange line). The efficiency was obtained by multiplying the quotient of theoretical power and total power by 100. The obtained efficiency is 72.55% which meets the 60% requirement. 72.55% efficiency is significant because higher efficiency translates to more range traversed by the e-bike given the same amount of charge.

4. CONCLUSIONS

The research successfully developed an adaptive speed and power motor control algorithms for a pedal-assisted e-bike via the proportional-integral control developed in Infineon's XMC1302 microcontroller. The adaptive speed control targets a specific speed set by the user and was found to have a percentage error of 9.62% which is in line with the objective of having less than 10% error for targeting speed. Likewise, adaptive power was achieved in all three different modes of the e-bike: Executive, Mid, and Sports. All obtained data regarding target power had less than a 10% error which is also in line with the objectives. Specifically, Executive had a percentage error of 2.54%, Mid had a percentage error of 4.14% and Sports had a percentage error of 9.08%.

Efficiency was also an important aspect to consider in the research because it determines how well the energy in the battery is utilized. For example, if a system had an efficiency of 50% it may traverse 20km, but if the efficiency was improved to 100%, it can traverse 40km under the same charge. The data from the research determined that the e-bike has an efficiency of 72.55% which meets the objective of having an efficiency of at least 60%. However, there were several spikes in Figure 8 where the efficiency dipped below 60% due to the acceleration of the e-bike since the power losses during acceleration are higher (Markowitz, 2017). 72.55% is a good result because most commercial BLDC motors from the market typically have an efficiency of around 80% ("Determining Electric Motor Load and Efficiency", 2017). As for the future directives of the system, the next step would be to improve the mobile application for the electric bicycle which can store different trips and predict the battery life of the system which would help the user determine which routes are most efficient and when the battery of the electric bicycle should be recharged.

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