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Research paper



Real time analysis of an intelligent torque controller for a hybrid bicycle

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Abstract

Most of the means of transportation is based on Internal Combustion engines, since they are fast and furious means of transportation. But bicycles are also relevant nowadays since they are the ideal means of the short commutation and which also helps in improving the human health by serving as a work out machine. But in our busy life bicycles are not preferred due to the uneven terrains. Electric bikes are the solution for this issue. Pedal assist sensor (PAS) based hybrid bicycle are also available, which will intermittently turn on and control the speed of electric drive based on the pedal crank speed. Thus there the electric drive assistance will be provided based on the speed of the pedal cranking. The real assistance should be provided when our torque requirement is needed. This paper deal with a novel sensor which sends the effort required at the pedal by the rider and intelligently control the electric drive so as to meet the required torque. The advantage of this controller is that the rider need to give only the same effort at the pedal irrespective of the terrain variations for a constant speed ride. A Fuzzy Logic Controller (FLC) is proposed here. The performance of the controller is simulated and analysed with the experimental results to prove the efficacy of the proposed technique.

1. Introduction

In search of newer and newer means of transportation for maintaining faster human life newer and newer auto mobiles were introduced day by day. Most of the advanced automobiles are using fossil fuels as their primary energy source with advanced control techniques. The extensive use of automobiles has led to hazardous environmental pollution and a lot of health related issues due to lack of exercises. A hybrid electric bicycle [3] will be one of the solutions to these problems. Hybrid means, the load will be shared by the rider and the electric motor. Automobiles are usually recommended due to its easiness and comfort. If this comfort and easiness can be achieved by a hybrid electric bicycle, then the demand for the same will be enormous.

Different control of a hybrid bicycle has been tried earlier such as PAS, in which the electric drive assistance will be employed when the pedal cranking speed is increased. A fuzzy logic controller [1] was also tried to control the voltage input to the motor as per the pedal torque and the error in speed. In this method the bulkiness of the system consisting of large batteries, in-compatibility of the Permanent Magnet dc (PMDC) motor used and a less efficient chain tension sensor are the disadvantages. To overcome these problems, a compatible Brushless dc (BLDC) hub motor is proposed with lithium ion battery. In this proposed work a contactless tension sensor is designed for sensing pedal effort applied by the rider during the ride. The technical performance of a dc drive electric bicycle is evaluated in [2], where the control strategy is not automated. In [4] modelling and control of electric motor drives are discussed which provides ne accounts on modelling and control aspects of BLDC motors. A deep understanding on the working and construction of BLDC motor is presented in [5] along with the sensor-less control of BLDC motor. It also discusses on the realization of BLDC motor drives with drive circuits. Various applications of BLDC motors on electric bicycle are also discussed in [5]. The dynamic modelling of electric bicycle and various comfort riding conditions are discussed in [6]. Modelling and simulation of BLDC motor drives are presented in [7]. The dynamic model of BLDC motor is detailed in [8] and in [9], the different aspects of modelling are also discussed. This paper aims to develop a strategy to control the speed of the motor with respect to the pedal efforts applied by the rider. The controller requires pedal torque as one of the inputs. For this a sensor is required which gives a voltage signal corresponding to the pedal torque as one input to the controller. The other input is the speed of the vehicle. So, based on the torque demand by the rider on the pedal and the actual speed of the bicycle, the PWM duty ratio of the controller is modified so as to run the BLDC motor to assist the riding. In this paper, a novel sensor is also proposed to properly sense the effort required at the pedal by the rider and the designed intelligent controller will then turn on the electric drive at the required speed and torque. So, irrespective of the terrain, the rider needs to give only a constant (unchanging) effort at the pedal. The controller chosen here is a Fuzzy Logic Controller (FLC). Different riding profiles are analysed and the ability of low-cost drives to serve the commuting purposes with moderate driving styles are also discussed in this paper. This paper is organized as follows: Section II. explains the method for selection of BLDC motor. The mathematical modeling of the bicycle is explained in Section III. The controller design strategy and the concepts of FLC used in the design is given in Section IV. Section V explains the experimental setup and the hardware implementation. Section VI deals with results and its analysis. The design and development of electronic circuits used are also detailed. Conclusions are presented in Section VII.

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2. BLDC motor selection

Motor Selection

The BLDC motor has been selected as the electric drive in this work, due to its high efficiency, good reliability, compactness, lower susceptibility to mechanical wear, high starting torque, less electrical noise, high range of operation and long lifespan. A load test of the BLDC motor has been carried out and the data are shown in Table-1. From the load test data, the characteristics of BLDC motor is analyzed and performance plots are as shown in Fig-2, Fig-3 and Fig-4.

Voltage	Current	P_{in}	Torque	Speed	P_{out}	Eff	Time
V	A	W	Nm	rpm	W	%	S
36.64	1.21	44.33	0.2	247.4	6.424	14.5	4
36.63	1.577	57.79	0.9	245.6	23.66	40.9	10
36.61	2.222	81.36	1.8	242.3	45.46	55.9	16
36.57	3.802	139	4.2	235.2	102.8	74	25
36.5	6.068	221.5	7.5	225	175.8	79.4	34
36.44	7.908	288.2	10.4	216.6	235.9	81.8	40
36.41	8.993	327.4	12.1	211.7	267.9	81.8	43
36.35	11.3	410.8	15.7	202.4	333.1	81.1	49
36.29	13.98	507.2	19.7	192.1	395.5	78	55
36.25	16.81	609.3	24	181.3	456.3	74.9	61
36.2	20	724	28.9	169.9	513.3	70.9	67
36.14	23.36	844.3	34	157.9	561.4	66.5	73
36.03	28.9	1041	41.7	138.2	603.3	57.9	82
35.9	35.66	1280	50.4	115.3	608.6	47.5	91

Figure 1: Table-1 Load test data

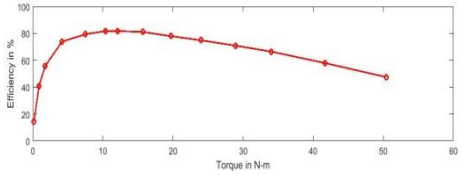


Figure 2: Efficiency vs Torque

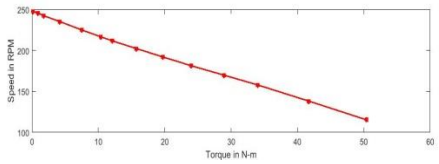


Figure 3: Speed vs Torque

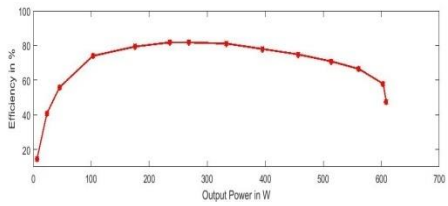


Figure 4: Efficiency vs Output power

By analyzing the characteristics of the BLDC motor, it is evident that the BLDC motor provides a maximum efficiency of 81:8 % at a speed of 211 rpm and at an output power of 268 watts. Based on the above test result, it is found that the selected motor is suitable for the electric bicycle, since it has high efficiency at maximum torque conditions and the torque-speed characteristics are linear as shown in Fig-3.

3. Bicycle modelling

The objective is to model a hybrid electric bicycle powered by a BLDC motor. The force exerted by the rider on the pedal of the bicycle is the source of bicycle movement [2][5] and the torque acting on the pedal is directly proportional to the power.
Different forces acting on a bicycle is shown in Fig-5. The torque acting on the pedal is

$$T_{pedal=}F_1R_1 \quad (1)$$

$$F_2 = \frac{R_2}{R_1}F_1 \quad (2)$$

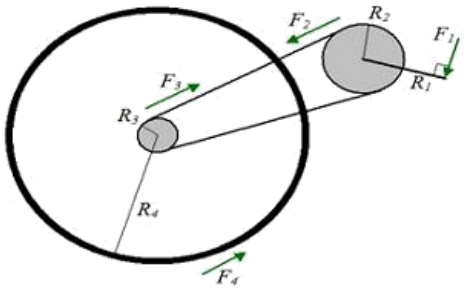


Figure 5: Forces acting on a bicycle

The torque acting on the rear wheel is

$$T_{wheel} = R_3F_2 \quad (3)$$

$$F_4 = \frac{T_{wheel}}{R_4} \quad (4)$$

Power at pedal

$$P_{pedal} = T_{pedal}\omega_{pedal} \quad (5)$$

Power at rear wheel

$$P_{wheel} = T_{wheel}\omega_{wheel} \quad (6)$$

where ω_{pedal} and ω_{wheel} are the pedal shaft angular velocity and rear wheel shaft angular velocity respectively.
F_1 is the force at the pedal, F_2 is the tractive force, F_3 is the reaction force, R_1 is the length of the crank, R_2 is the radius of the chain wheel, R_3 is the radius of the rear sprocket and R_4 is the radius of rear wheel. Power at the pedals is proportional to the power at rear wheel.

Motor Dynamics

Modelling of BLDC motor is done as in [3] and [4] using the three phases, under the assumptions that all the three phases are symmetric and rotor being non-salient type, the rotor reluctance does not change with angular displacement. For all the phases, the mutual inductances and self inductances are also assumed to be symmetric.
The relations governing the dynamics of a BLDC can be expressed as follows. The electromagnetic torque equation is given by

$$T_e = [e_ai_a + e_bi_b + e_ci_c] /\omega \quad (7)$$

where e_a, e_b and e_c are the respective back emfs of the three phases a, b and c; i_a, i_b and i_c are the three phase currents and ω is the angular velocity of the rotor.
The dynamics of the mechanical part is given by

$$T_e - T_l = B\omega + J\frac{d\omega}{dt} \quad (8)$$

where T_l is the load torque acting on the motor shaft, B is the coefficient of friction of the motor and J is the moment of inertia of the motor.

4. Controller Design

In this Section, the controller for the switching of BLDC motor is designed based on fuzzy logic, so as to provide assistance to the rider.

The rider's e ort to ride is evaluated based on the output from the torque sensor. Depending upon these sensed inputs such as speed and pedal torque , the controller estimates the required motor torque and speed, and take proper control action to drive the motor as per the torque requirements on the road. This control action reduces the rider's e ort.

Since the control action required is a non-linear one, Fuzzy logic controller will be the best choice here. In short FLC will control the speed of the motor, by sensing the pedal torque and actual speed of the bicycle. he control rules are already framed in the rule base of FLC, hence can be called as an intelligent controller.

Fuzzy Logic Controller

A Fuzzy control system is a control system based on Fuzzy logic mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0 (true or false). The term "Fuzzy" refers to the fact that the logic involved can deal with concepts that cannot be expressed as "true" or "false" but rather as "partially true". Fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans. Fuzzy controller consists of an input stage, a processing stage, and an output stage. The input stage maps sensor inputs, to the appropriate membership functions and truth values. The processing stage invokes each appropriate rule and generates a result for each, then combines the results of the rules. Finally, the output stage converts the combined results back into a specific control output value.

Design of Fuzzy Logic Controller

The Fuzzy logic controller designed is basically a sugeno type, in which there are two inputs (speed and pedal torque) and one output (PWM duty ratio). Five gaussian membership functions for each inputs, namely very low (VL), low(L), medium(M), high(H) and very high (VH) are chosen. Similarly five linear membership functions such as VL pedal torque are measured by two different sensors, processed and fed towards the micro controller. There it is digitalised and taken towards the FLC module. The fuzzy rules adopted are as shown in the table-1.

Table 1: Fuzzy Rule

Speed ⇨ pedal torque	VL	L	M	H	VH
VL	VL	VL	VL	VL	VL
L	L	L	L	VL	VL
M	M	M	M	L	VL
H	H	H	M	L	VL
VH	VH	VH	H	M	L

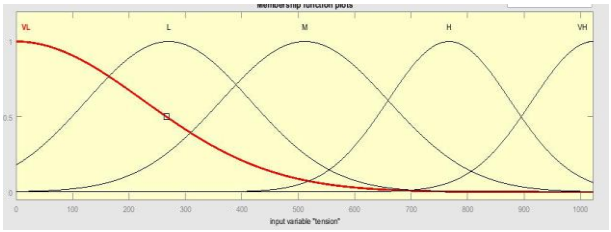


Figure 6: Input variable speed tuned as shown to get the control surface as shown in figure 8

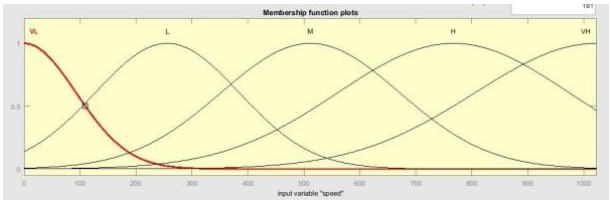


Figure 7: Input variable tension tuned as shown to get the control surface as shown in Fig- 8

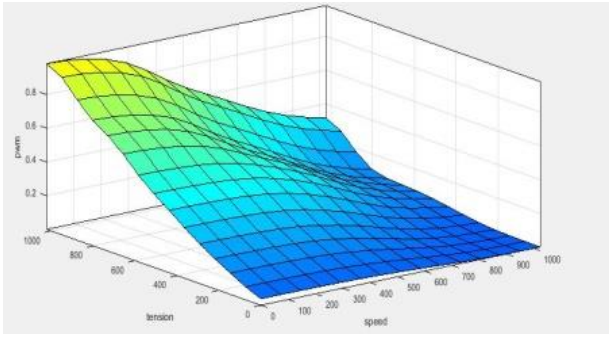


Figure 8: Control surface after tuning the inputs

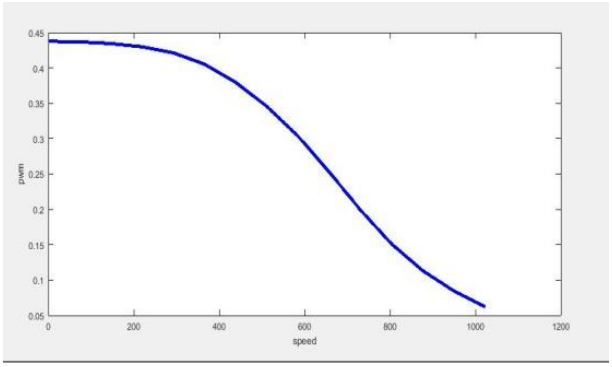


Figure 9: Plot showing the relationship between speed and PWM output after tuning

5. Experimental setup and hardware implementation

The experiment is conducted on a bicycle. A novel and cheap pedal torque sensor, which measures the pedal torque in terms of chain tension is shown in Fig-15. It uses an inductance coil and a core. The displacement of chain corresponding the pedal torque is measured as inductance variations, by different core positions along the length of the inductance coil. This inductor is kept in an oscillating circuit which generates frequency modulated signals corresponding to the pedal torque variations. Similarly by using a hall sensor and a micro controller the actual speed of the bicycle is measured. These two inputs are taken towards the FLC for the control action

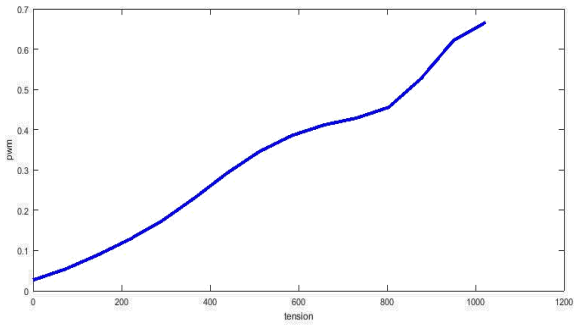


Figure 10: Plot showing the relationship between chain tension and PWM output after tuning

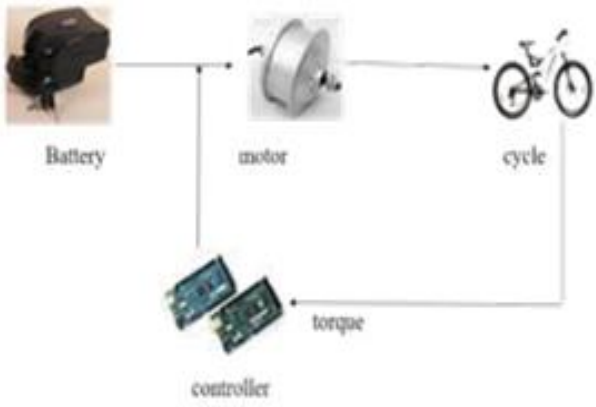


Figure 11: General block diagram

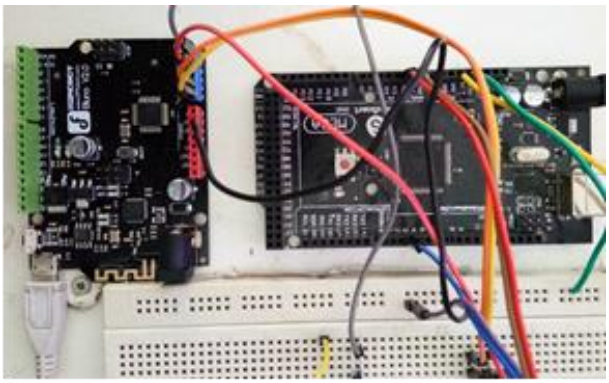


Figure 12: FLC and Bluetooth communication module

Experimental setup

Major components of the system are battery, BLDC hub motor, a bicycle, sensors and the controller with blue tooth low energy (BLE) communication. The general block diagram is as shown in Fig-11. The controller used for FLC is shown in the Fig-12. The experimental setup made is as shown in Fig-13.

Hardware implementation

For the experiment, a special arrangement is made which allows the bicycle at different angle positions. The signals are captured by the microcontroller and communicated through BLE module. The data was received by an Android based software installed in the smart phone. These captured data are used for the ne tuning of FLC. Thus it is made much more intelligent.



Figure 13: Experimental set up

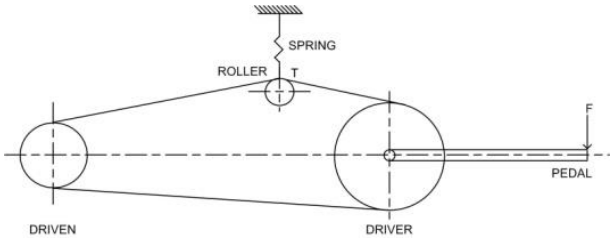


Figure 14: Schematic diagram of sensor arrangement



Figure 15: Side view of sensor arrangement

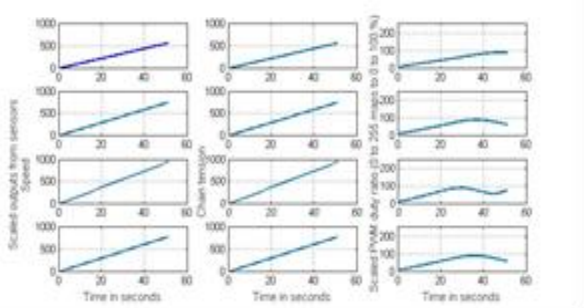


Figure 16

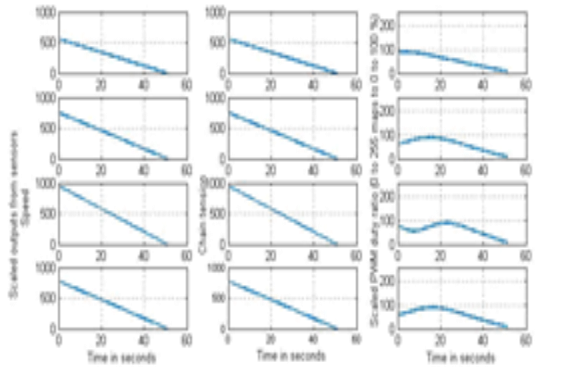


Figure 17

6. Results and analysis

This chapter describes the results obtained while testing the already designed FLC for different practically sensible cases. The experimental setup consists of two input signals correspond to speed and chain tension. The FLC here is the previously designed one and embed-ded on a microcontroller. The output of FLC is plotted against time. The following are the cases adopted for the analysis.

Case 1

In this case both the speed and chain tension are assumed to be increasing at slopes 5^0,10^0,15^0 and 20^0 respectively. Corresponding to each slope pwm waveforms are obtained at the 3rd column of the array, as shown in Fig-16.

Case 2

In this case both the speed and chain tension are assumed to be decreasing at slopes 5^0,10^0,15^0 and 20^0 respectively. Corresponding to each slope PWM waveforms are obtained at the 3rd column of the array, as shown in Fig-17.

Case 3

In this case the speed is increasing at slopes 5^0,10^0,15^0 and 20^0 respectively, and the chain tension is assumed to be decreasing at slopes 5^0,10^0,15^0 and 20^0 respectively. Corresponding to each combination pwm waveforms are obtained at the 3rd column of the array, as shown in Fig-18.

Case 4

In this case the speed is decreasing at slopes 5^0,10^0,15^0 and 20^0 respectively, and the chain tension is assumed to be increasing at slopes 5^0,10^0,15^0 and 20^0 respectively. Corresponding to each combination pwm waveforms are obtained at the 3rd column of the array, as shown in Fig-19.

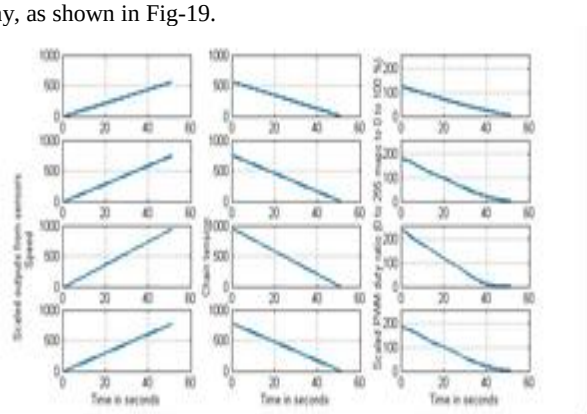


Figure 18

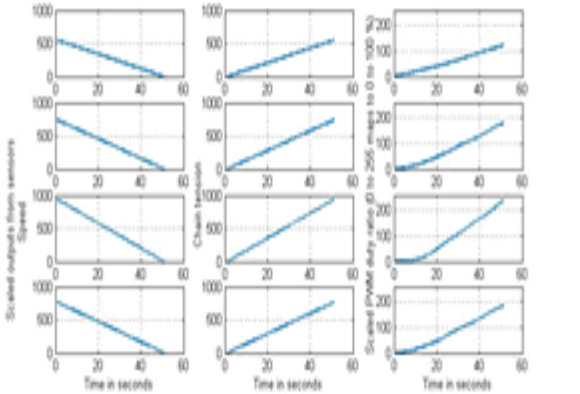


Figure 19

Case 5

In this case the speed is assumed to be constant and the chain tension is assumed to be increasing at slopes 5^0,10^0,15^0 and 20^0 respectively. Corresponding to each combination pwm waveforms are obtained at the 3rd column of the array, as shown in Fig-20.

Case 6

In this case the speed is assumed to be constant and the chain tension is assumed to be decreasing at slopes 5^0,10^0,15^0 and 20^0 respectively. Corresponding to each combination pwm waveforms are obtained at the 3rd column of the array, as shown in Fig-21.

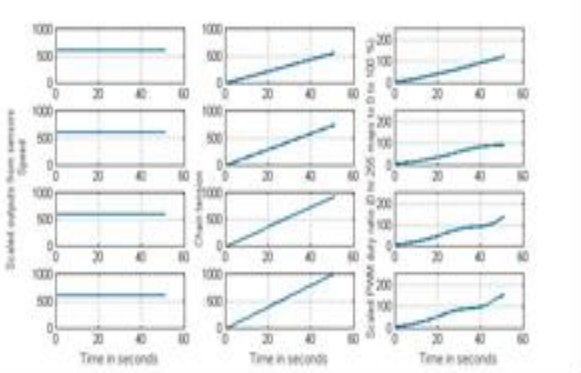


Figure 20

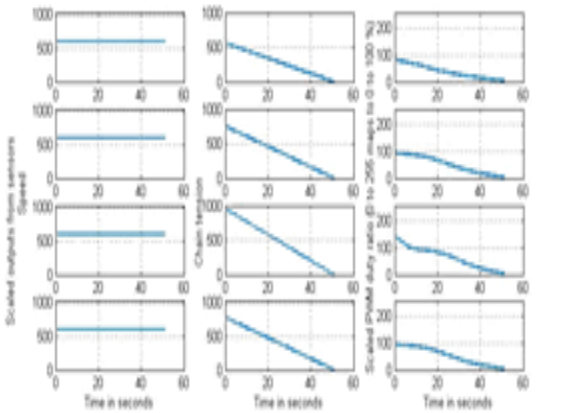


Figure 21

Case 7

In this case the speed is assumed to be increasing at slopes 5^0,10^0,15^0 and 20^0 respectively. and the chain tension is assumed to be constant. Corresponding to each combination pwm waveforms are obtained at the 3rd column of the array, as shown in Fig-22.

Case 8

In this case the speed is assumed to be decreasing at slopes 5^0,10^0,15^0 and 20^0 respectively and the chain tension is assumed to be constant. Corresponding to each combination pwm waveforms are obtained at the 3rd column of the array, as shown in Fig-23.

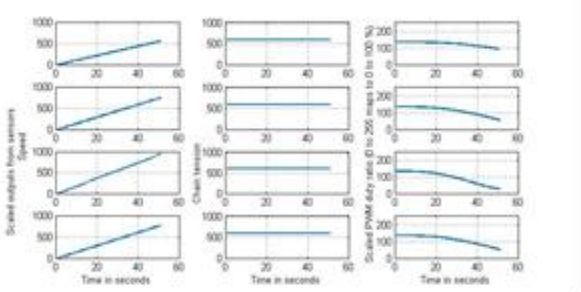


Figure 22

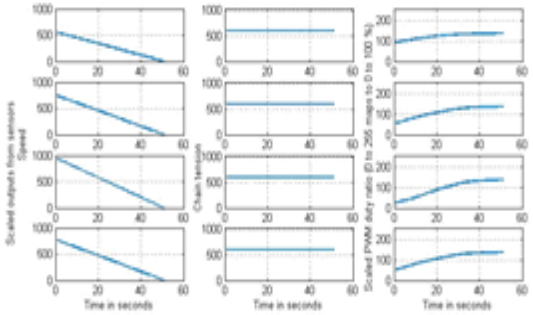


Figure 23

7. Conclusion

In this paper, an intelligent embedded controller using Fuzzy logic controller for a hybrid electric bicycle has been designed and implemented successfully. A novel sensor is proposed in this work which properly senses the e ort required at the pedal by the rider and the designed intelligent controller turns on the electric drive at the required speed and torque. The sensor arrangement for measuring the pedal torque using an inductance coil-core variation is designed, it has been calibrated and implemented in this work. Both from the simulation results and experimental results it is proved that the controller has successfully controlled the bicycle torque depending upon the input from the pedal torque sensor

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