Design of a fuzzy-based controller for electric vehicles on Indian roads

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The manuscript was received on 24 December 2004 and was accepted after revision for publication on 31 July 2006.

DOI: 10.1243/09596518JSCE123

Abstract: This paper presents a novel approach with a rule-based acceleration control strategy for electric vehicles. This proposal has a straightforward goal for minimizing the complexities of the existing controllers used in vehicles. The use of fuzzy logic enables the heuristic rule-based technique to be used, as an efficient solution. The fuzzy logic controller designed here is a combination of fuzzy decision maker and fuzzy speed controller. The fuzzy decision maker is designed in such a way that it takes into account the battery's state of charge, speed, type of terrain, road load, brake, acceleration, and gear as input parameters, which gives the reference speed to the fuzzy speed controller according to the changing situations. The fuzzy speed controller is designed for the d.c. chopper-fed drive for the seperately excited motor. The fuzzy logic controller determines the vehicle speed according to the scenarios in Indian road conditions. Simulation results would specify the performance of the new proposed fuzzy controller. The results have been compared with the conventional controller proportional integral. From the results it has been inferred that the range of the vehicle has been increased, with less error in speed, with the fuzzy logic controller, than with the classical proportional integral controller. This controller has also been implemented in the embedded chip, field programmable gate array (FPGA) and results shown experimentally, which is the future vehicle.

Keywords: electric vehicle, fuzzy logic controller, driver speed command, driver brake command, load, state of charge, gear, terrain, driving conditions

1 INTRODUCTION

Recent advances in battery and motor technologies have radically transformed electric vehicles, which previously were used for certain limited applications only. With the use of a high-energy-density battery and a high-efficiency motor-drive system, the driving range increases. Electric vehicles [**1**, **2**] have now reached the level where they present virtually no problems as a practical means of transportation for commuting, shopping trips, and other uses. The progress in battery and motor technologies has made it possible for electric vehicles not only to extend their field of usage but also to exploit fully the advantages of motor-based propulsion.

The electric vehicle [**3**, **4**] is an integration of vehicle body, electric propulsion, energy storage battery, and energy management. The storage battery voltage is dependent on the charge and load current. Hence the motor [**5**] should be capable of handling these fluctuations in supply voltage in order to drive the vehicle efficiently.

The present work involves the design of an intelligent controller using the fuzzy logic technique. Figure 1 shows the overall architecture of the electric vehicle with the proposed fuzzy logic controller. In recent years, many modern control techniques have been proposed. An emerging technology such as fuzzy logic [**6**, **7**] has been applied, because the controller could interpret the dynamics of the system operation, and adjust accordingly. This work predicts the performance of the vehicle on various types of terrain as applicable to Indian conditions.

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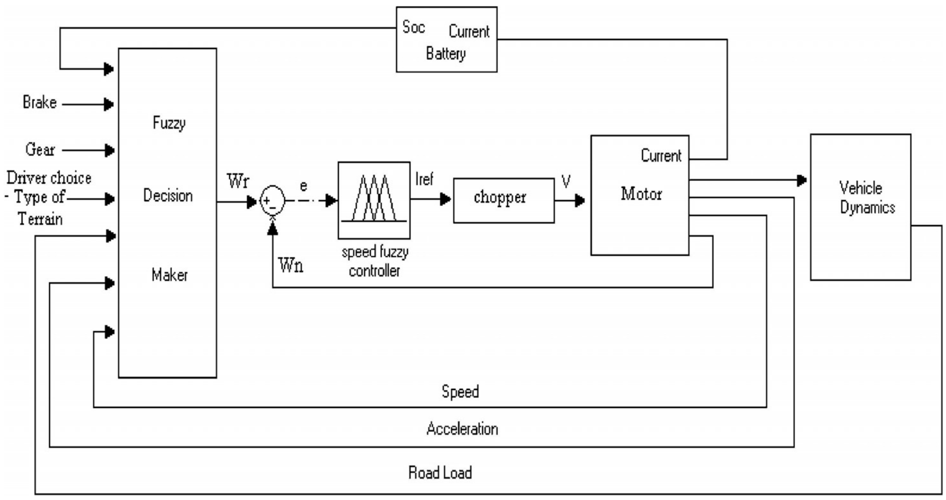


Fig. 1 Overall architecture of the electric vehicle

2 DEVELOPMENT OF THE TRANSFER FUNCTION MODEL FOR THE ELECTRIC VEHICLE

The transfer function model has been developed for the electric vehicle and includes vehicle dynamics [**8**], road dynamics, and motor parameters. The armature controlled shunt-type d.c. motor is coupled with the electric vehicle. The torque developed in the motor is proportional to the product of the armature current and air gap flux given as

$$T_{\mathrm{M}} = K_1 K_{\mathrm{f}} i_{\mathrm{f}} i_{\mathrm{a}} \tag{1}$$

where

K_1 = constant
K_{f} = constant
i_{f} = field current
i_{a} = armature current

In the armature-controlled d.c. motor, the field current is kept constant and equation (1) can be written as

$$T_{\mathrm{M}} = K_{\mathrm{T}} i_{\mathrm{a}} \tag{2}$$

where

K_{T} = motor torque constant from equation (1)

The back e.m.f. of the motor is proportional to speed and is given as

$$e_{\mathrm{b}} = K_{\mathrm{b}} \frac{\mathrm{d}\theta}{\mathrm{d}t} \tag{3}$$

where

K_{b} = back e.m.f. constant

The armature circuit differential equation is

$$L_{\mathrm{a}} \frac{\mathrm{d}i_{\mathrm{a}}}{\mathrm{d}t} R_{\mathrm{a}} i_{\mathrm{a}} + e_{\mathrm{b}} = e \tag{4}$$

The torque equation is

$$J \frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} + f_0 \frac{\mathrm{d}\theta}{\mathrm{d}t} = T_{\mathrm{M}} = K_{\mathrm{T}} i_{\mathrm{a}} \tag{5}$$

Taking the Laplace transform of equations (3) to (5), assuming zero initial conditions, the equations derived are

$$E_{\mathrm{b}}(s) = K_{\mathrm{b}} s \theta(s) \tag{6}$$

$$(L_{\mathrm{a}} s + R_{\mathrm{a}}) L_{\mathrm{a}}(s) = E(s) - E_{\mathrm{b}}(s) \tag{7}$$

$$(Js^2 + f_0 s)\theta(s) = T_{\mathrm{M}}(s) = K_{\mathrm{T}} I_{\mathrm{a}}(s) \tag{8}$$

From equations (6) to (8), the transfer function of the system is obtained as

$$G(s) = \frac{K_{\mathrm{T}}}{s[(R_{\mathrm{a}} + sL_{\mathrm{a}})(Js + f_0) + K_{\mathrm{T}} K_{\mathrm{b}}]} \tag{9}$$

The voltage applied to the armature circuit is $E(s)$ which is opposed by the back e.m.f. $E_{\mathrm{b}}(s)$. The net voltage $(E - E_{\mathrm{b}})$ acts on a linear circuit that consists of resistance and inductance in series, having the transfer function $1/(sL_{\mathrm{a}} + R_{\mathrm{a}})$. The result is an armature current $I_{\mathrm{a}}(s)$. For a fixed field, the torque developed by the motor is $K_{\mathrm{T}} I_{\mathrm{a}}(s)$. This torque developed rotates the load of the motor at a speed of $\dot{\theta}(s)$ against the moment of inertia of the motor, J, the moment of inertia of the vehicle, I_{v}, and the viscous friction with coefficient f_0 and rolling resistance coefficient f_{r} for various terrains. The transfer function of the vehicle is

$$\frac{1}{(J+I_v)s+(f_0+f_r)} \tag{10}$$

As the motor is coupled with the vehicle, the vehicle parameters have to be accounted for. The factors employed are the moment of inertia and the various rolling resistances for the terrain, e.g. smooth, rough, or medium hard. The terrains considered are according to the Indian road conditions. The moment of inertia of the vehicle is another factor. The vehicle inertia is

$$I_v \frac{R_{fd}(T_{out}-T_{load})}{N_w} \tag{11}$$

where

N_w = wheel speed
R_{fd} = final drive ratio
T_{load} = load torque

After including the vehicle inertia and rolling resistance the transfer function becomes

$$\frac{1}{I_v s+f_r} \tag{12}$$

The back e.m.f. signal $E_b=K_b\dot{\theta}(s)$ is calculated from the shaft speed. The angular displacement $\theta(s)$ is obtained by integrating the shaft speed $\dot{\theta}(s)$, according to

$$\frac{\dot{\theta}(s)}{E(s)}=\frac{K_T/L_a}{(J+I_v)s^2+s(f_0+f_r)+K_TK_b/L_a} \tag{13}$$

where

I_v = vehicle inertia (kg m^2)
f_r = rolling resistance
J = moment of inertia of the motor (kg m^2)
f_0 = viscous friction coefficient of the motor (N m/rad s)
K_T = torque developed by the motor (N m)
K_b = back e.m.f. constant

and where R_a/L_a is negligible.

The armature circuit inductance L_a is usually negligible. Therefore from equations (11) and (12) the transfer function of the armature controlled electric vehicle is simplified as shown in equation (13). The road dynamics include the rolling resistance, which has various values for different terrains. The transfer function will vary as the road dynamics change.

In this work, the equivalent model for equation (13) is taken as

$$G(s)=\frac{0.913\,242}{1.39s^2+1.215s+0.913\,242} \tag{14}$$

3 DESIGN OF THE PROPORTIONAL–INTEGRAL CONTROLLER

A controller produces an output signal consisting of two terms: one proportional to the actuating signal and the other proportional to its integral. Such a controller is called a proportional–integral (PI) controller. Transfer functions have been developed for various road conditions such as smooth, rough, uphill, and downhill. The response of the transfer functions changes with the road dynamics. The transfer functions for different terrains have been tuned using the PI controller [**9**]. The closed-loop system response is found to meet the desired specifications. Figure 2(a) shows the block diagram of the speed control system for an electric vehicle (with adjustable terrain).

Among the various terrain transfer functions developed, the transfer function for the smooth terrain has been shown here and the PI controller is tuned to obtain the desired performance. Figure 2(b) shows the block diagram of the speed control system for an electric vehicle (in smooth terrain). Figure 2(c) shows the response of the control loop with PI controller for the smooth terrain without a fuzzy decision maker. Because of the non-linear and time-variant nature of motor drives [**10**], it is difficult to meet these objectives under different operating conditions using fixed parameters. One of the adaptive controllers such as a fuzzy logic controller has been employed to achieve better control even under varying parameters.

The fuzzy model is one that uses linguistic variables to describe the input and output to perform a fuzzy operation on the inputs for generating the output. Since this controller model is based on the Mamdani type of fuzzy controller, it uses a composition-based inference mechanism, which combines all the rules into an aggregated system output and determines the final non-fuzzy control value.

4 DESIGN OF THE FUZZY DECISION MAKER

The proposed fuzzy decision maker is discussed below. The input parameters of the fuzzy decision maker are as follows:

(a) acceleration;
(b) state of charge of the battery;
(c) speed;
(d) road load;
(e) terrain;
(f) gear;
(g) brake.

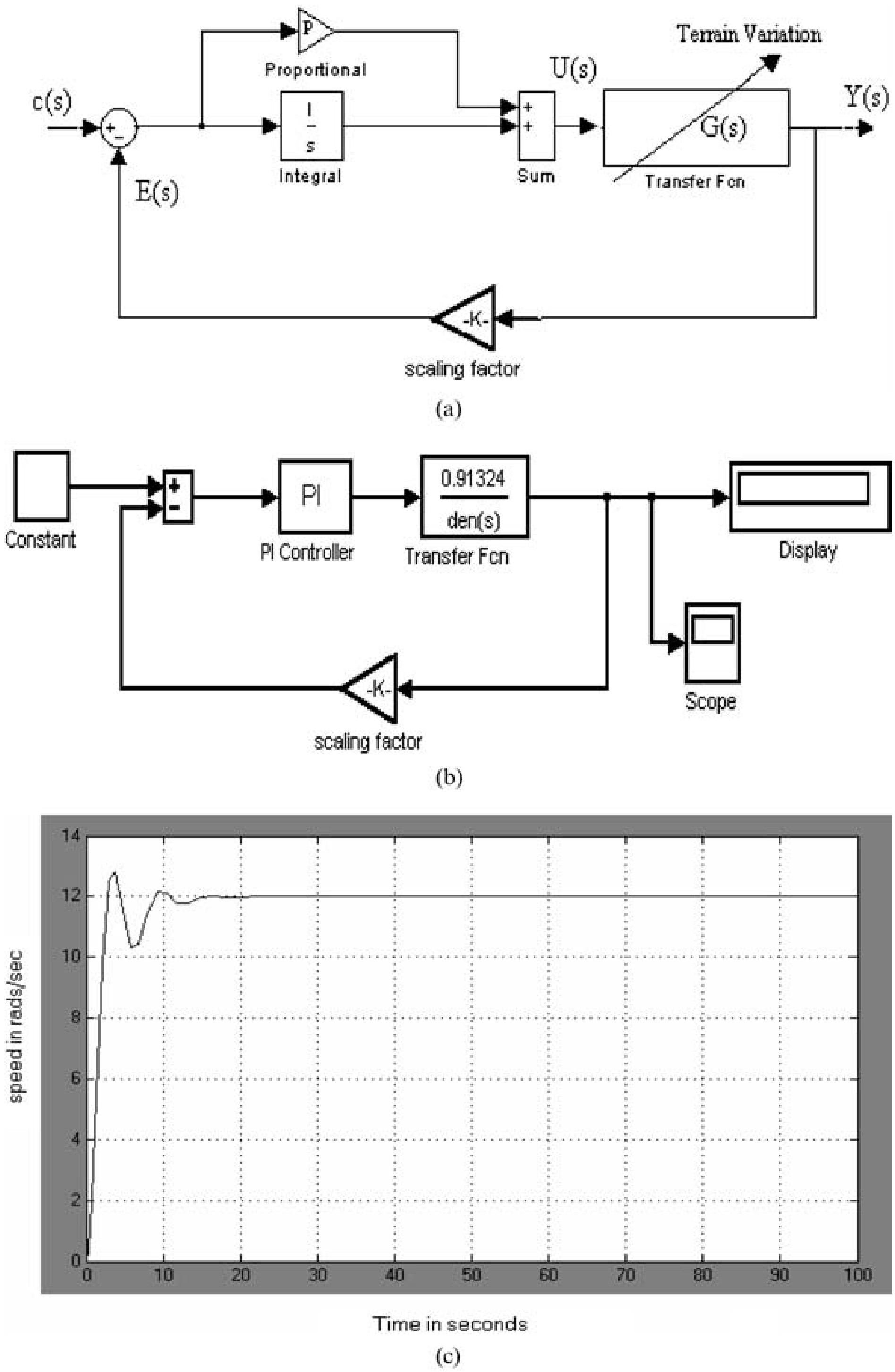


Fig. 2 Block diagrams of the speed control systems for (a) the electric vehicle (with adjustable terrain) and (b) the electric vehicle (in smooth terrain) without the fuzzy decision maker. (c) Response of the control loop with the PI controller for smooth terrain without the fuzzy decision maker

The output of the fuzzy decision maker is the voltage, whose value ranges from 0 to 240 and their linguistic variables are classified as very low, low–medium, medium, high, and very high. It is converted into speed using the voltage–speed equation of the d.c. motor. The input to the speed fuzzy controller from the fuzzy decision maker is the reference speed. The design of the fuzzy controller is designed on the basis of the controlled variable-speed error and change in error. The characteristic of this controller is that it is able to drive the system to the set point within the minimum time and without large overshoot.

The inputs for the fuzzy controller are the speed error $e_{\omega}(n) = \omega_{r}^{*}(n) - \omega_{r}(n)$ and the change in speed error $\Delta e_{\omega}(n) = e_{\omega}(n) - e_{\omega}(n-1)$. The output variable is the current, which has been transmitted to the chopper to drive the motor.

The range of the speed error is from -150 to 150 and its linguistic variables are considered as negative, zero, and positive, whereas the change in speed error range is from -10 to 10 and its linguistic variables are selected as negative saturated, negative large, negative small, positive large, positive small, and positive saturation. The output variable is the current whose range is 0–30 and its linguistic variables are chosen as zero, positive large, positive small, and positive saturation.

The ranges of the brake and acceleration parameters are considered as 0–5 where 5 is the maximum value and their linguistic variables are selected as low, medium, and high.

The vehicle's speed range is 0–240, represented by five linguistic variables such as very low, low, low–medium, medium, and high. The gear command value ranges from 0 to 5, with the fourth gear as maximum speed and the fifth gear as the reverse gear. The range of the state of charge of the battery has been taken as 0–1, where the maximum charge is taken as 1 and is represented by three variables as low, normal, and high. A range of 0–100 is assigned to the load of the vehicle, which includes the linguistic variables as low, low–medium, medium, and high. The range of 0.001–0.4 is assigned for the terrain parameter. The typical characteristics of Indian terrain are taken into consideration. The different terrains chosen are smooth, rough, uphill, and downhill. The vehicle runs at an optimum speed based on the driving speed on various terrains.

The membership function for the state of charge is shown in Fig. 3. The linguistic variable of the fuzzy sets 'normal' represents the actual range 0.2–0.7 of the state of charge, 'low' represents the intermediate range 0–0.4 between 'normal' and 'low', and 'high' represents the range 0.5–1.

5 RULE BASE OF THE FUZZY DECISION MAKER

The important part of the fuzzy decision maker is the formation of rules to synchronize all the parameters to get the desired output. The rules have been formed on the basis of the Indian driving conditions, the vehicle dynamics characteristics, and the motor parameters. The control action of the fuzzy decision maker is mainly based on the parameters of the vehicle, such as the charge level of the battery, the road load of the vehicle, the acceleration, the speed, and the appropriate gear which helps the vehicle to run at optimum speed. When any one of these parameters change, the controller helps the vehicle to adapt and perform according to the new parameters.

In this case, the fuzzy decision maker predicts the motor speed at which the vehicle can run. Sets of different rules are developed for each terrain. The fuzzy decision maker output is based on the evaluation of the rules using the fuzzy inference system. Table 1 shows the rule base created for the condition when smooth terrain is selected. All the rules are executed in parallel. The values indicated inside parentheses represent the weights of the rules.

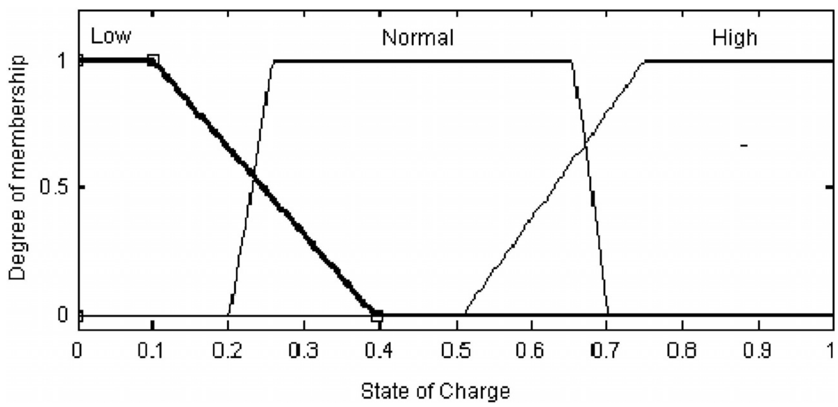


Fig. 3 Membership function for the state of charge of the battery

Table 1 Rule base when the terrain is smooth (terrain, smooth; speed, medium; acceleration, high)

	Speed for the following loads			
State of charge	Low	Low–medium	Medium	High
High	Low (1)	Low–medium (0.15)	High (0.7) Very high (0.85)	High (0.95)
Normal	Medium (0.65)	High (0.8)	Very high (0.9)	Very high (0.6)

6 COMPARISON OF THE PERFORMANCE OF THE FUZZY CONTROLLER AND PROPORTIONAL–INTEGRAL CONTROLLER FOR THE TRANSFER FUNCTION WITH THE FUZZY DECISION MAKER

The fuzzy logic controller module takes into account the parameters such as the state of charge, speed, acceleration, load, and terrain, and the output of this fuzzy logic controller is the driving speed. The electric vehicle system combined with fuzzy logic controller has an improved and an efficient system performance. The transfer function of the electric vehicle modelled is as explained in section 2 and includes road dynamics and vehicle dynamics. Figures 4(a) and (b) show a block diagram of the speed control system for the electric vehicle (in smooth terrain) with the fuzzy decision maker.

Figure 4(c) shows the response of the control loop with the PI controller for the smooth terrain with the fuzzy decision maker, whereas Fig. 4(d) shows the response of the control loop with the fuzzy logic controller. The result of the fuzzy logic controller shows that the designed fuzzy logic is robust enough to load changes and road grade changes.

7 COMPARISON OF THE PERFORMANCE OF THE FUZZY CONTROLLER AND PROPORTIONAL–INTEGRAL CONTROLLER WITHOUT THE TRANSFER FUNCTION WITH THE FUZZY DECISION MAKER

The performance of the conventional controller is that it takes a longer time to reach the desired destination. The speed error response depicts that there is an error, whereas the performance of the fuzzy logic controller depicts that it can cover a longer distance in a very short period of time. The error in speed follows a smooth response. The integral square error value is found to be less in the proposed fuzzy logic controller than in the conventional controller.

Figures 5(a) and (b) depict the speed variation for changes in terrain with the fuzzy logic controller (triangular membership function) and plot of error in speed for changes in terrain with the fuzzy logic controller (triangular membership function). Figures 5(c) and (d) depict the speed variation for changes in terrain with the fuzzy logic controller (trapezoidal membership function) and plot of error in speed for changes in terrain with the fuzzy logic controller (trapezoidal membership function). From the triangular and trapezoidal fuzzy logic responses it can be inferred that the integral square error value is less in the trapezoidal fuzzy logic controller. Figures 5(e) and (f) depict the speed variation for changes in terrain with the conventional controller and plot of error in speed for changes in terrain with the conventional controller.

8 PERFORMANCE OF THE FUZZY LOGIC CONTROLLER

The control action of the fuzzy logic controller is discussed for various terrains in India. The typical characteristics of the different Indian terrains have been taken into consideration, such as smooth, rough, uphill, and downhill. For each type of terrain, i.e. when the terrain changes, the input parameters taken into account also change accordingly as it is self-adaptive and includes all the possible parameters of the vehicle. The controller acts under various driving speeds and terrains respectively such as smooth, rough, uphill, and downhill during the course of travel. The results are taken during the simulation. One of the cases is discussed below.

8.1 Smooth terrain

When the vehicle runs on a smooth terrain, the first, second, third, and fourth gears are applicable and the speed of the vehicle is only between 40 and 60 km/h according to the Indian driving conditions. The average speed in city driving conditions is 33 km/h.

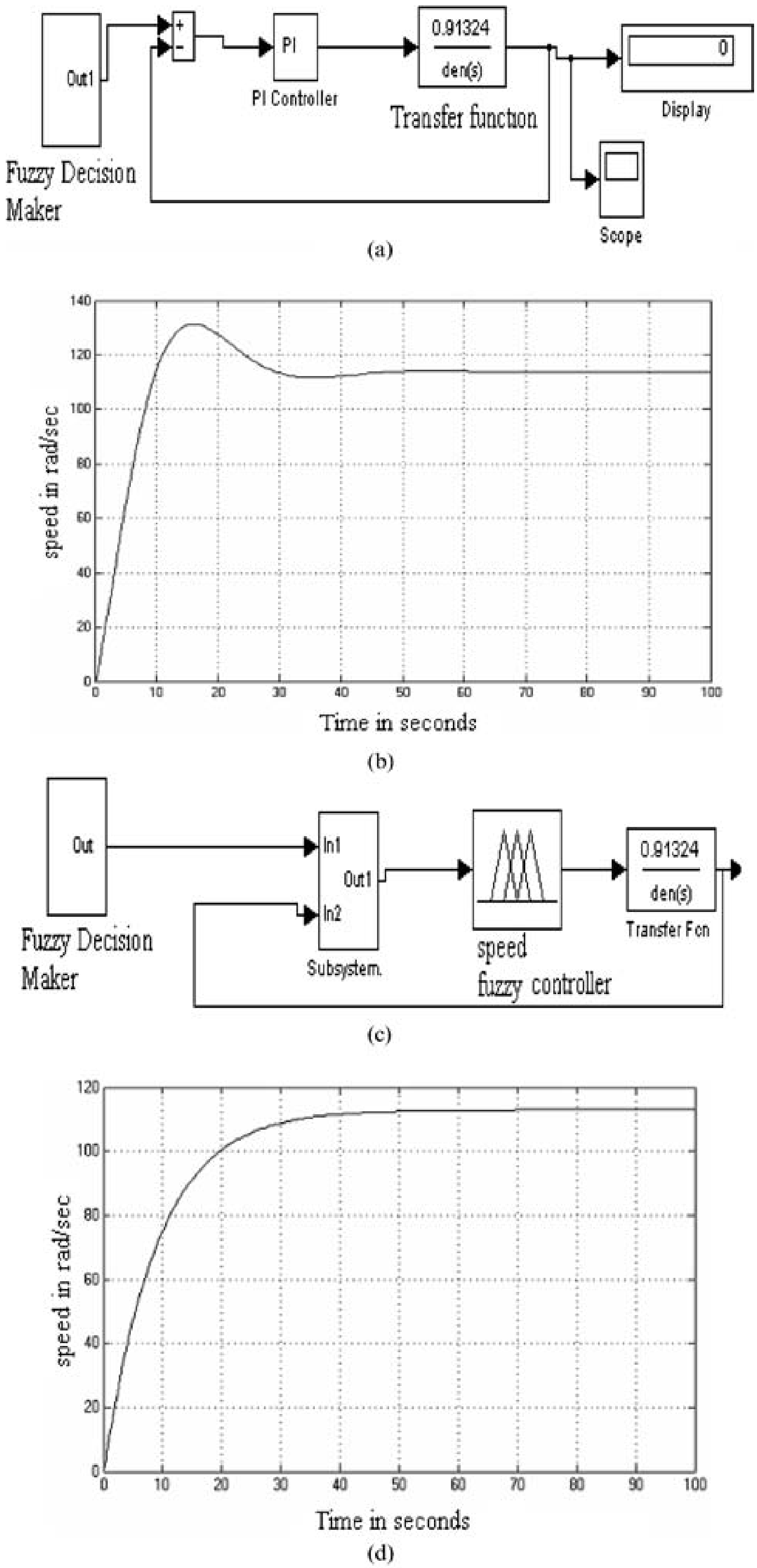
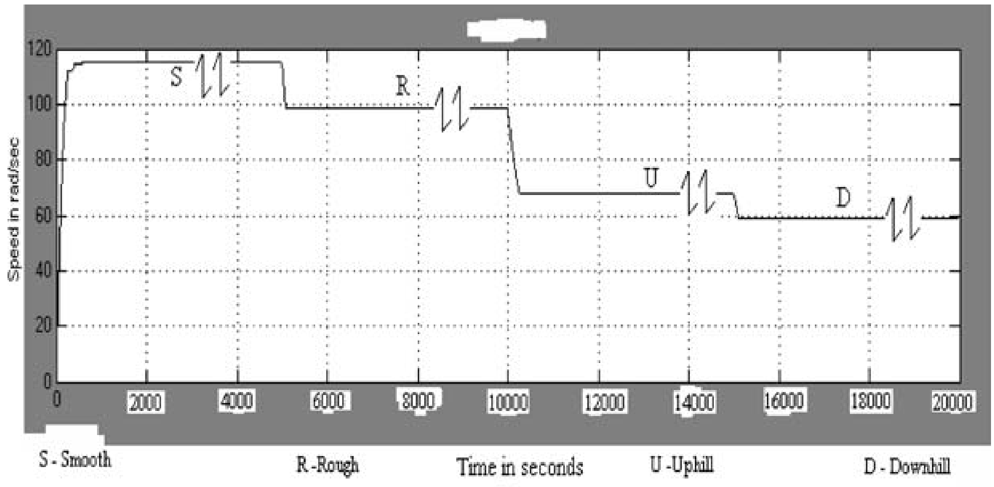
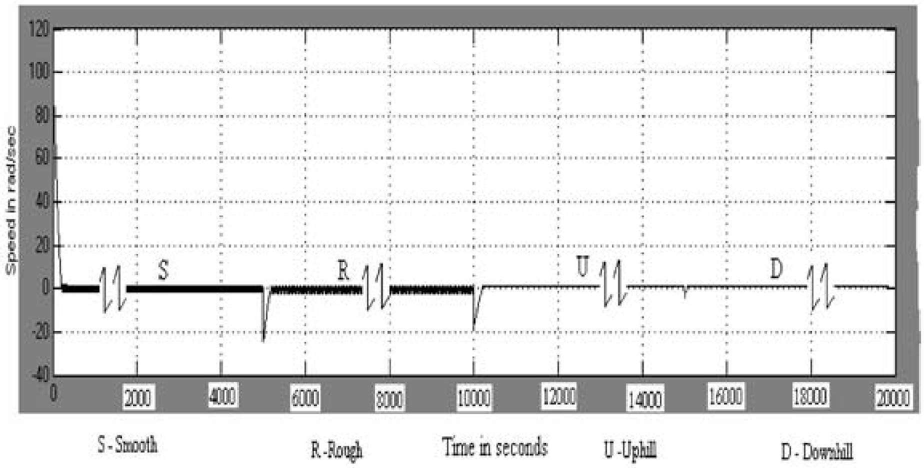


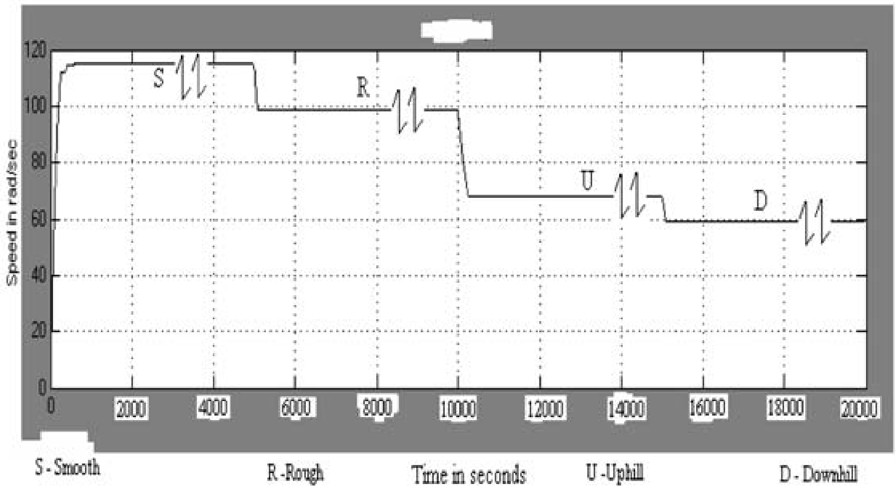
Fig. 4 (a) Block diagram of the speed control system for the electric vehicle (in smooth terrain) with the fuzzy decision maker. (b) Response of the control loop with the PI controller for smooth terrain with the fuzzy decision maker. (c) Block diagram of the speed control system for the electric vehicle (in smooth terrain). (d) Response of the control loop with the fuzzy logic controller for smooth terrain



(a)

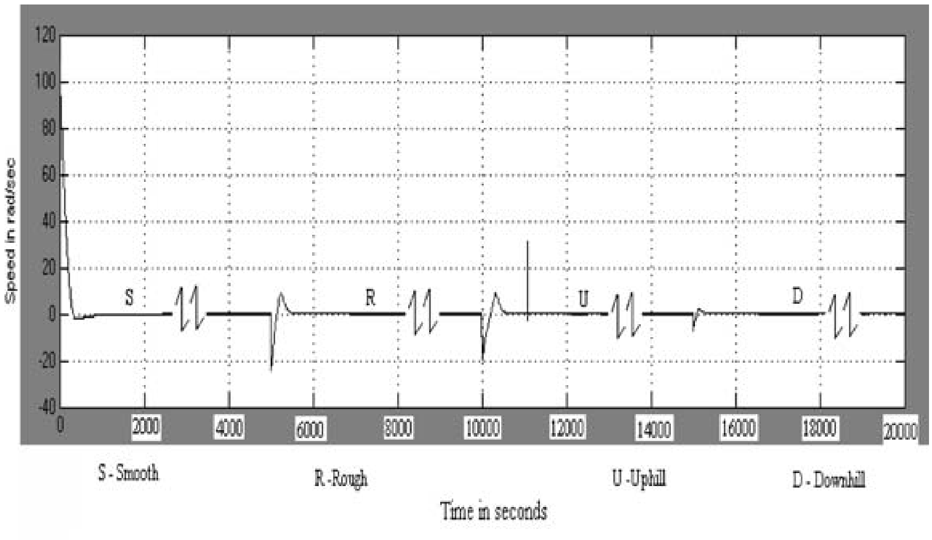


(b)

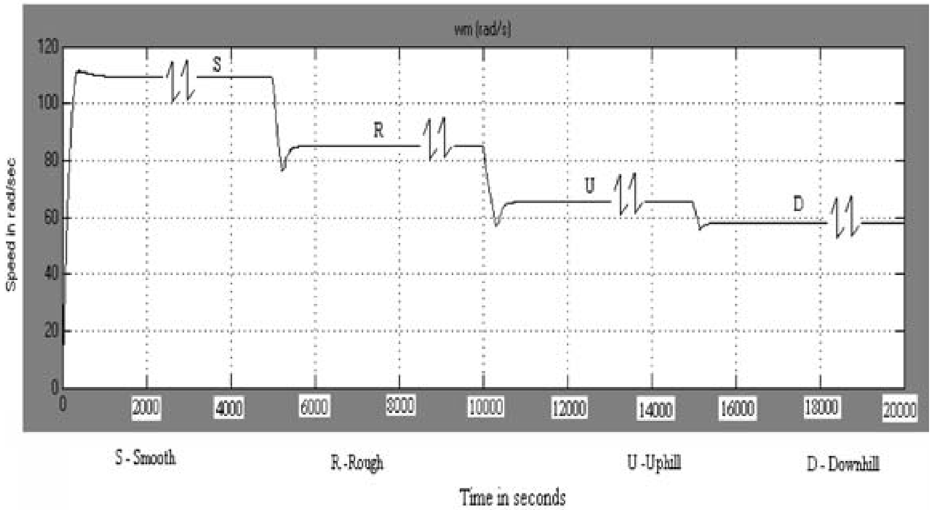


(c)

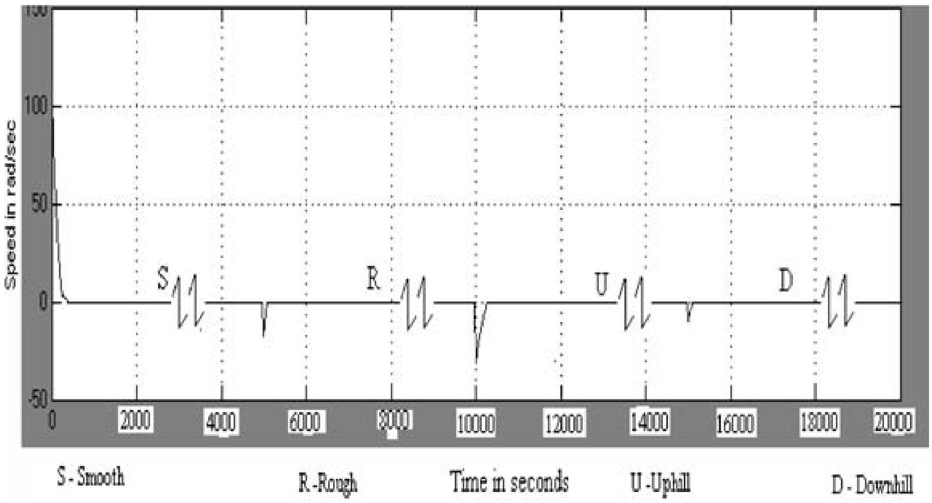
Fig. 5 (a) Speed variation for changes in terrain with the fuzzy logic controller (triangular membership function). (b) Plot of the error in speed for changes in terrain with the fuzzy logic controller (triangular membership function). (c) Speed variation for changes in terrain with the fuzzy logic controller (trapezoidal membership function). (d) Plot of the error in speed for changes in terrain with the fuzzy logic controller (trapezoidal membership function). (e) Speed variation for changes in terrain with the conventional controller. (f) Plot of the error in speed for changes in terrain with the conventional controller



(d)



(e)



(f)

Fig. 5 (Continued)

In normal mode, when the state of the charge is high, the load is low, the speed is very low, and the acceleration is low, the first gear is selected; then the set speed for the fuzzy logic controller is very low. The motor runs at a set speed for the fuzzy logic controller of 43 rad/s, and the vehicle runs at a speed of 18 km/h.

In normal mode, when the state of charge is high, the load is low–medium, the speed is normal, and the acceleration is low, the second gear is considered; then the set speed for the fuzzy logic controller is low. The motor runs at a set speed for the fuzzy logic controller of 50 rad/s, and the vehicle runs at a speed of 32 km/h.

In normal mode, when the state of charge is high, the load is low–medium, the speed is normal, and the acceleration is medium, the third gear is chosen; then the set speed for the fuzzy logic controller is low–medium. The motor runs at a set speed for the fuzzy logic controller of 55 rad/s, and the vehicle runs at a speed of 45 km/h.

In normal mode, when the state of charge is normal, the load is medium, the speed is normal and the acceleration is high, third gear is selected; then the set speed for the fuzzy logic controller is medium. The motor runs at a set speed for the fuzzy logic controller of 65 rad/s, and the vehicle runs at a speed of 30 km/h.

In normal mode, when the state of charge is low, the load is high, the speed is high, and the acceleration is high, the four gear is considered; then the set speed for the fuzzy logic controller is high. The motor runs at a set speed for the fuzzy logic controller of 75 rad/s, and the vehicle runs at a speed of 61 km/h.

9 SIMULATION RESULTS

The states of charge of the battery for both the conventional controller and the proposed fuzzy logic controller were estimated. The range of the vehicle has been calculated by estimating the amount of charge utilized by the battery according to the specification. For each terrain segment the $I_{\mathrm{r.m.s.}}$ value of the armature current of the motor has been calculated. From that it is inferred that on running the controller for nearly 5 h the charge consumed by the conventional controller is 80 per cent whereas using the fuzzy controller it is only 65 per cent. A range of 75 km is achieved using the fuzzy logic controller but by means of conventional controller the range is found to be only 70 km.

Figure 6(a) shows the speed variations for changes in terrain with the fuzzy logic controller and Fig. 6(b) depicts the speed variations for changes in terrain with the conventional controller for a duration of 5 h.

10 SINGLE-CHIP REALIZATION OF THE INTEGRATED FUZZY DECISION MAKER–CONTROLLER USING A FIELD-PROGRAMMABLE GATE ARRAY

Figure 7(b) depicts the realization of an integrated fuzzy decision maker which consists of a field-programmable gate array chip [**11**], analogue-to-digital converter, and toggle switches for the inputs, and a d.c. motor and liquid-crystal display for the output. The parameters taken for the hardware implementation are the speed, acceleration, brake, and state of charge of battery, gear, and terrain. The output of the fuzzy system is the duty cycle of the pulse width modulation signal given to the motor. The implementation process is subdivided into three components, namely fuzzifier, rule base, and defuzzifier. The design procedure consists of the following steps as shown in Fig. 7(a):

(a) identifying the system's input and output, their universes of discourse, and their membership function that convert crisp values into fuzzy values;
(b) identifying the rules of interference and the method of interference (correlation minimum and correlation product) that maps fuzzy inputs to fuzzy outputs;
(c) determining the defuzzification method, which transforms the fuzzy output to a crisp output based on the output membership function.

The function of the fuzzifier is to transform crisp inputs into fuzzy inputs.

Crisp inputs for the accelerator, brake, and battery are an 8-bit binary value representing the current reading, a 3-bit binary value for the gear, and a 2-bit binary value for gear and stream of pulses for speed. The first step is to convert the crisp inputs to fuzzy inputs [**12**]; for this, the crisp inputs are compared with the membership function parameters of the variables respectively. Rule evaluation is the second step of the fuzzy logic process, and it determines the response to a given set of input values. A rule base for this system is created. The rule evaluation method used was 'minimum–maximum' inferences, since it takes the minimum of the antecedents to determine

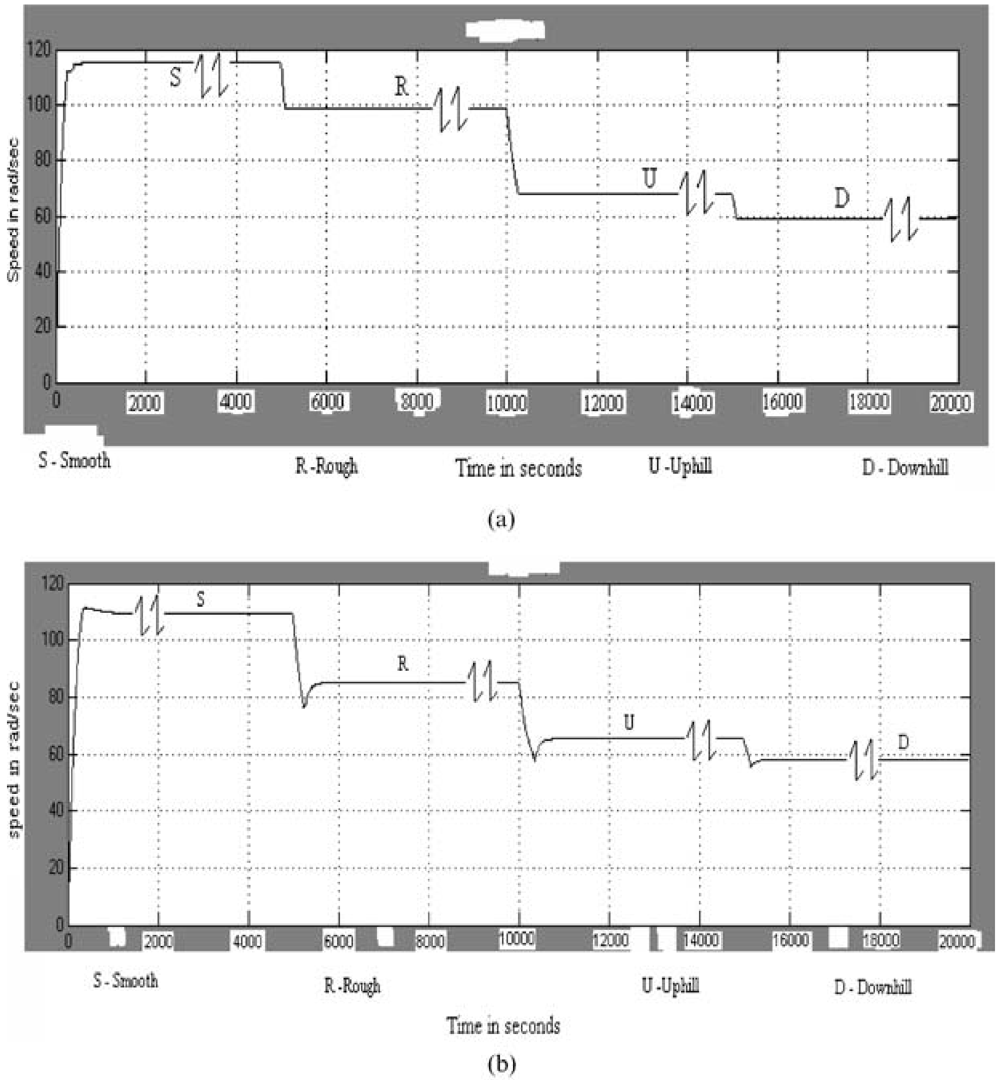


Fig. 6 Speed variations for changes in terrain (a) with the fuzzy logic controller and (b) the conventional controller

rule strength for each consequent to determine fuzzy outputs.

Defuzzification is the last step in the fuzzy logic [**13**] process, which transforms the fuzzy outputs to a crisp output based on the output membership function. In defuzzification, all significant outputs combine into a specific comprehensive result to obtain a crisp output. One of the most common defuzzification techniques such as the centre-of-area method or centroid method is used in the present study because it yields a lower mean square error than a fuzzy logic controller based on the mean-of-maximum method. The centre-of-area method aids calculation of the centre of gravity, and moreover this method is chosen since it is of importance that the values do not change much between two consecutive samples.

All the modules are integrated and synthesized using the Xilinx project navigator and support tools. The synthesized very-high-speed integrated circuit hardware description language (VHDL) [**14**] source code is placed and routed. Finally, a bit file is created. The bit file is fused into the Xilinx XC2S300E-6PQ208 field-programmable gate array [**15**] and interfaced with the input and output devices.

The motor is tested for various terrains and gear conditions respectively. Initially, the system is in neutral gear for smooth terrain, with the available battery status, with no acceleration and braking. To start the system, the first gear is chosen and the motor runs at the minimum speed. To increase the speed of the motor the gear position is changed consecutively. The vehicle can switch over from one terrain to another by setting it initially. The module

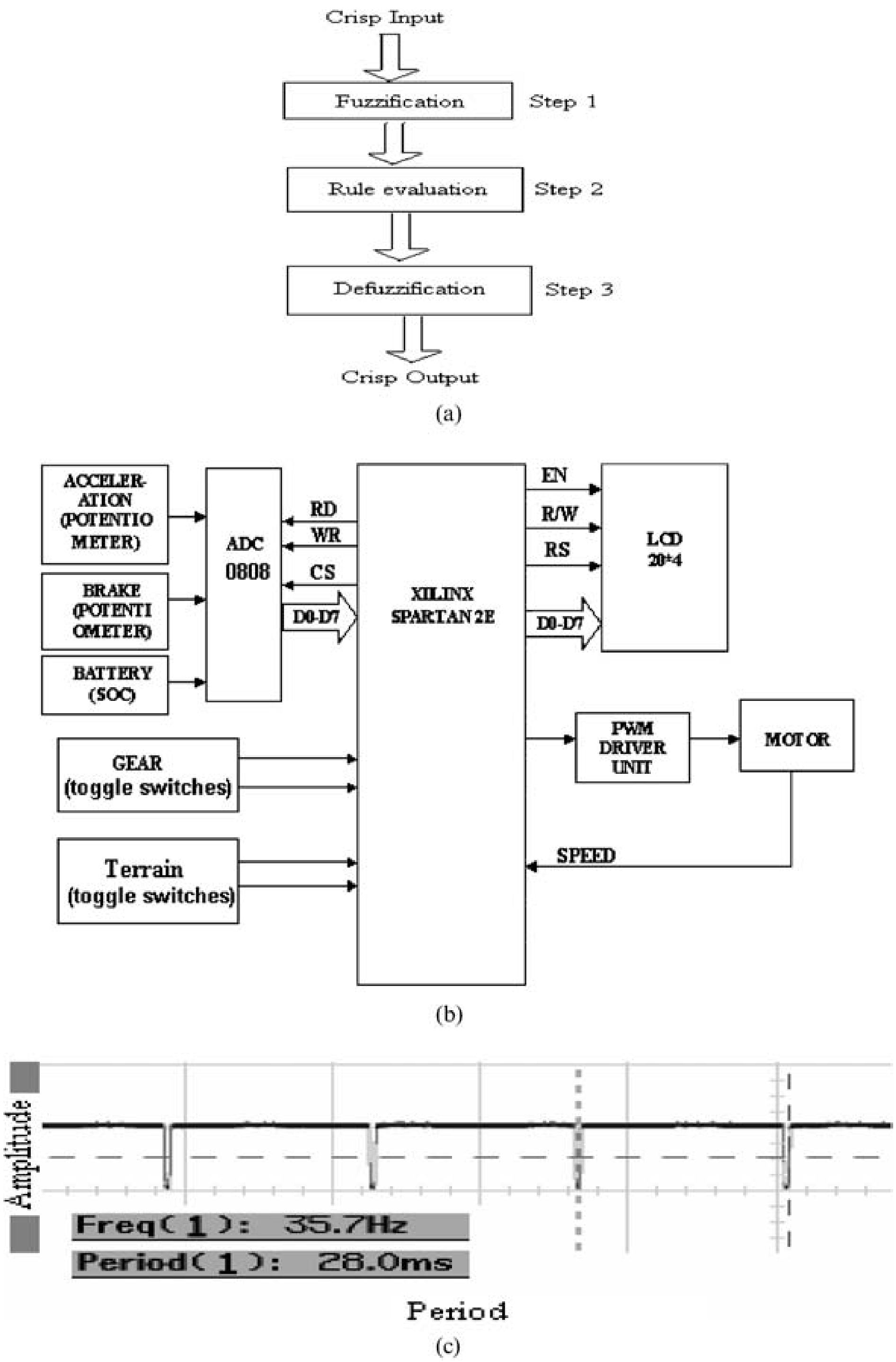


Fig. 7 (a) Fuzzy logic process algorithm. (b) Hardware interface (SOC, state of charge; ADC, analogue-to-digital converter; RD, read; WR, write; CS, chip select; EN enable; R/W, read–write; RS, read select; LCD, liquid-crystal display; PWM, pulse width modulation). (c) Pulses from the motor for 100 per cent duty cycle input

has been checked for assorted input conditions. One such case is dealt with here. When the terrain is smooth, the state of charge is high, the acceleration is nil, the braking is nil, the gear is in fourth position and the speed is in the range 00–FF, then the output duty cycle is 100 per cent pulse width modulation signal generated for this output, and this signal is given to the motor.

The feedback from the motor is measured using a CRO (Cathode Ray Oscilloscope), as shown in

Table 2 Experimental results of the d.c. motor for different terrains

Duty cycle (%)	Speed (r/min)	Period (ms)	Terrain
100	2120	28	Smooth
70	1640	39	Rough
50	500	70	Uphill
30	300	80	Downhill

Fig. 7(c). It is inferred from Fig. 7(c) that the motor takes 28 ms to complete 1 rev. In this condition, the motor runs at a speed of 2127 r/min. Table 2 shows the experimental results for different terrains. Using this controller, the motor can be controlled up to a maximum speed of 2127 r/min for smooth terrain, 1640 r/min for rough terrain, 500 r/min for uphill terrain, and 300 r/min for downhill terrain.

11 CONCLUSIONS

A new methodology has been adopted which has the straightforward goal of achieving better performance by taking into account more relevant factors of the vehicle's primary characteristics such as the speed, the acceleration, the brake, the gear, and the state of charge and secondary characteristics such as terrain and the road load. The use of fuzzy logic enables the rule-based approach to adapt to the operating constraints.

The performance of different terrains with the PI controller were analysed for variance in the following combinations:

(a) the PI controller with a transfer function;
(b) the PI controller with the fuzzy decision maker.

The response of the controller is found to have a peak overshoot and it takes more time to settle at the settling point compared with the fuzzy logic controller.

Analysis was carried out using the fuzzy logic controller to obtain the performance of the control loop for various combinations:

(a) the fuzzy logic controller with a transfer function;
(b) the fuzzy logic controller with the fuzzy decision maker.

The results obtained show that, for the fuzzy logic controller, the response was smoother without any overshoot and settling time is faster than for the classical PI controller.

It has also been inferred from the responses of the speed variation for changes in terrain with the PI controller that its integral square error value is higher than with the fuzzy logic controller (trapezoidal and triangular membership functions).

Among the trapezoidal and triangular membership functions it is established that the use of the trapezoidal membership function is better.

The errors in speed for changes in terrain with the fuzzy logic controller and classical controller have been analysed. It has been observed from the integral square error method, that the error in speed for the PI controller is higher than the fuzzy logic error in speed value.

It is estimated that the vehicle would cover a distance of 75 km in the case of the fuzzy logic controller when compared with the conventional controller whose range is found to be 65 km.

Finally from the analysis it is concluded that the performance of the electric vehicle would be better with the fuzzy logic controller than with the classical PI controller as it has a longer range and less error in speed.

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