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A Fuzzy Logic Based Control Algorithm for EV Suspension Systems

Shaojia Huang¹, T.W. Ching², Wenlong Li³, Luwei Zeng⁴, K.T. Chau⁵ and C.C. Chan⁶

¹ *Zhuhai College of Jilin University, Zhuhai, China, jafield@yeah.net*

² *University of Macau, Avenida da Universidade, Taipa, Macau, twching@ieee.org*

³ *University of Hong Kong, Pokfulam Road, Hong Kong, wlli@eee.hku.hk*

⁴ *University of Macau, Avenida da Universidade, Taipa, Macau, mb55440@umac.mo*

⁵ *University of Hong Kong, Pokfulam Road, Hong Kong, ktchau@eee.hku.hk*

⁶ *University of Hong Kong, Pokfulam Road, Hong Kong, ccchan@eee.hku.hk*

Summary

This paper proposes a new semi-active suspension system to improve the ride comfort suitable for electric vehicles (EVs). A half car model based on air suspension system is introduced with different control strategies for the front and rear suspensions respectively. A fuzzy control strategy is implemented on the front wheel which will be used as the reference model for the rear wheel. A neural network (NN) controller integrated with neural network identification will be utilized to control the rear suspension. A numerical simulation based on MATLAB shows the advantages of attenuating the vibrations by the proposed control strategy.

Keywords: electric vehicle, control system, modelling, simulation, vehicle performance

1. INTRODUCTION

Suspension system is an important component for improving ride quality, boosting handling and optimizing road holding. As regards the controllability of the vehicle suspension, the suspension systems can be divided into three types: passive, semi-active and active. Obviously, the semi-active and the active types are controllable, which can ameliorate the suspension performance effectively. Therefore, skyhook control which is based on the velocity of the vehicle in vertical orientation was firstly introduced by Karnopp and Crosby [1] as semi-active suspension control method. Then the skyhook control was improved and optimized by grey box approach [2] which is derived from empirical data. With the help of some known control theory, the semi-active control can be augmented with optimal control such as linear-quadratic-regulator (LQR) and linear quadratic-Gaussian (LQG) [3, 4]. In order to acquire more information of road input and effective control performance, Bender firstly incorporate the preview strategy into active suspension [5]. The preview method can be separated into two categories, they are front preview and wheelbase preview, respectively. Due to the low cost and the effectiveness [6], the wheelbase preview method is always implemented on suspension systems. In this method, the rear suspension can obtain road information from the front suspension with an accelerometer amount on the un-sprung mass. However, due to the variability of road input and nonlinearity of suspension system in an operation process for a suspension system, the aforesaid control methods which greatly rely on the mathematical model and cannot deal with the real process

effectively. Nevertheless, some artificial intelligence methods have been implemented on active or semi-active suspension systems as these approaches rely less on concrete mathematical model. For example, Yoshimura *et al.* proposed a fuzzy logic based semi-active controller for vehicle suspension [6, 7], which is relied more on empirical data. A neural-network-based fuzzy controller in [8] was also proposed by Eslaminasab *et al.* to improve the suspension performance of heavy duty vehicles. A model reference control (MRC) is used originally developed to solve a problem which the performance specifications are given by a reference model. The MIT rule is the original approach to MRC. For half vehicle model, the front suspension performance can be regarded as a reference model for the rear suspension. Therefore, the future of the vehicle model such as the weight distribution and the spring stiffness will play a very important role for the controllability!

Usually, there are three types of weight distribution for passenger cars which are shown in Fig. 1. For electric vehicle (EV), the weight distribution is even than the internal combustion engine vehicle (ICEV) because of the battery packs are usually mounted evenly on the chassis. Besides, the front suspension performance such as the sprung mass acceleration will also influence the rear suspension. Considering the 1:1 weight distribution and similarity of front and rear suspension systems, a fuzzy based MRC method is proposed in this paper, particularly suitable EVs.

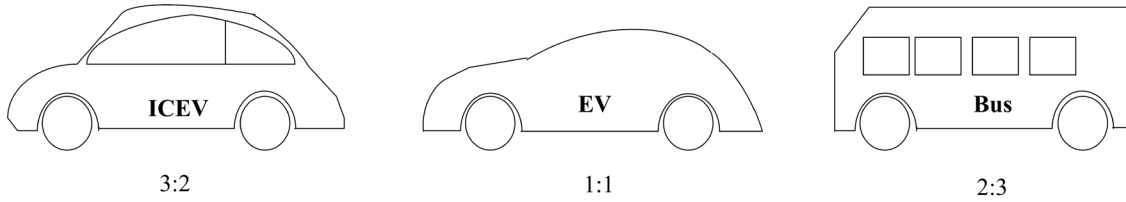


Figure 1: Weight distribution for different vehicles

In this paper, a fuzzy controller based on empirical knowledge is used to control the front suspension system. Then the control performance such as the sprung mass acceleration of front wheel will be introduced for the rear suspension system as a reference signal. The air suspension implemented in the system is used to attenuate the vibrations due to its good nonlinear characteristics. So this paper is organized as follow. A half EV suspension with air spring is introduced first, then the whole control strategy of the suspension system will be illustrated and the numerical results of the proposed method at different conditions will be compared. Finally, a summary will be presented.

2. Dynamic Model of Vehicle

In this section, a half EV model is established and is shown in Fig. 2.

According to the vertical movement of the front and rear wheels and the pitch motion of the vehicle body, the equations of the motion for the front and rear un-sprung mass, vehicle body vertical movement and the angular turning of the vehicle body are described below, respectively:

$$m_{1f}\ddot{Z}_{1f} = K_{gf}(Z_{0f} - Z_{1f}) - K_{af} \cdot (Z_{1f} - Z_{2f}) - C_f(\dot{Z}_{1f} - \dot{Z}_{2f}) - U_{p1} \quad (1)$$

$$m_{1r}\ddot{Z}_{1r} = K_{gr}(Z_{0r} - Z_{1r}) - K_{ar} \cdot (Z_{1r} - Z_{2r}) - C_r(\dot{Z}_{1r} - \dot{Z}_{2r}) - U_{p2} \quad (2)$$

$$M\ddot{Z}_c = -K_{af}(Z_{2f} - Z_{1f}) - K_{ar}(Z_{2r} - Z_{1r}) - C_f(\dot{Z}_{2f} - \dot{Z}_{1f}) - C_r(\dot{Z}_{2r} - \dot{Z}_{1r}) - U_{p1} + U_{p2} \quad (3)$$

$$I\ddot{\theta} = L_a [K_{af}(Z_{2f} - Z_{1f}) + C_f(\dot{Z}_{2f} - \dot{Z}_{1f}) + U_{p1}] - L_b [K_{ar}(Z_{2r} - Z_{1r}) + C_r(\dot{Z}_{2r} - \dot{Z}_{1r}) + U_{p2}] \quad (4)$$

$$\begin{cases} Z_{2f} = Z_c - L_a \theta \\ Z_{2r} = Z_c + L_b \theta \end{cases} \quad (5)$$

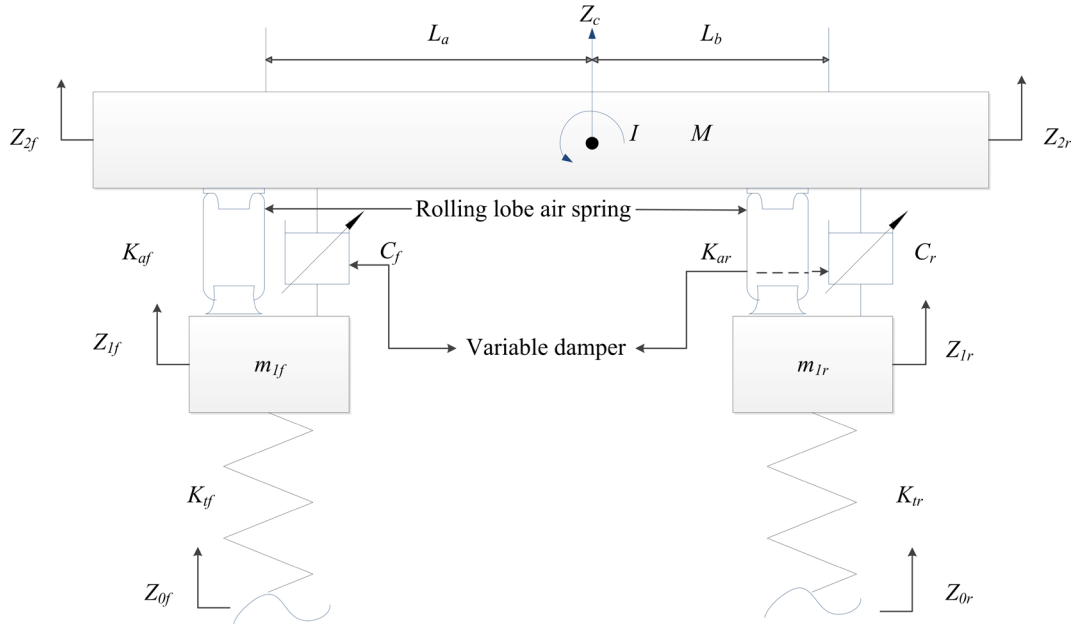


Figure 2: A half vehicle model

where U_{p1} and U_{p2} stand for the semi-active force from the front and rear suspension uttered by the fuzzy controller and the neural controller respectively. The front and the rear un-sprung mass are shown as m_{lf} and m_{lr} . K_{tf} , K_{tr} , K_{af} and K_{ar} are the stiffness of the front wheel, rear wheel, front suspension and the rear suspension. C_f and C_r are the damping ratio of the front and the rear dampers. Z_{0f} , Z_{0r} , Z_{1f} , Z_{1r} , Z_{2f} , Z_{2r} , Z_c and θ stand for the road input of the front and rear wheel, un-sprung and sprung mass movement of the front and rear suspension, the vertical motion of the vehicle body and the pitch angle of the vehicle, respectively.

Due to the nonlinear character of the air spring, it can be integrated into the EV suspension system. However, the stiffness of the air spring depends on the air pressure change rate inside the air bag and such change rate is coordinated with the effective area of the air bag. So the change rate of the effective area will be calculated first, followed by the frequency and the stiffness of the air spring. The derivation process is shown below,

$$\begin{cases} A = A_0 + \beta x \\ V = V_0 - \alpha x \\ (p + p_a)V^\gamma = (p_a + p_0)V_0^\gamma \end{cases} \quad (6)$$

Due to the fast response of the air bag, the air movement inside the air bag can be regarded as an ideal adiabatic process. Then the stiffness will be calculated below,

$$F = \left[(p_0 + p_a) \left(\frac{V_0}{V} \right)^\gamma - p_a \right] A \quad (7)$$

$$k = \frac{dF}{dx} = -A\gamma(p + p_a) \frac{1}{V} \frac{dV}{dx} + p \frac{dA}{dx} \quad (8)$$

3. Control Strategy

This section will introduce the control strategy of the whole system and the overall control flow process is shown in Fig. 3.

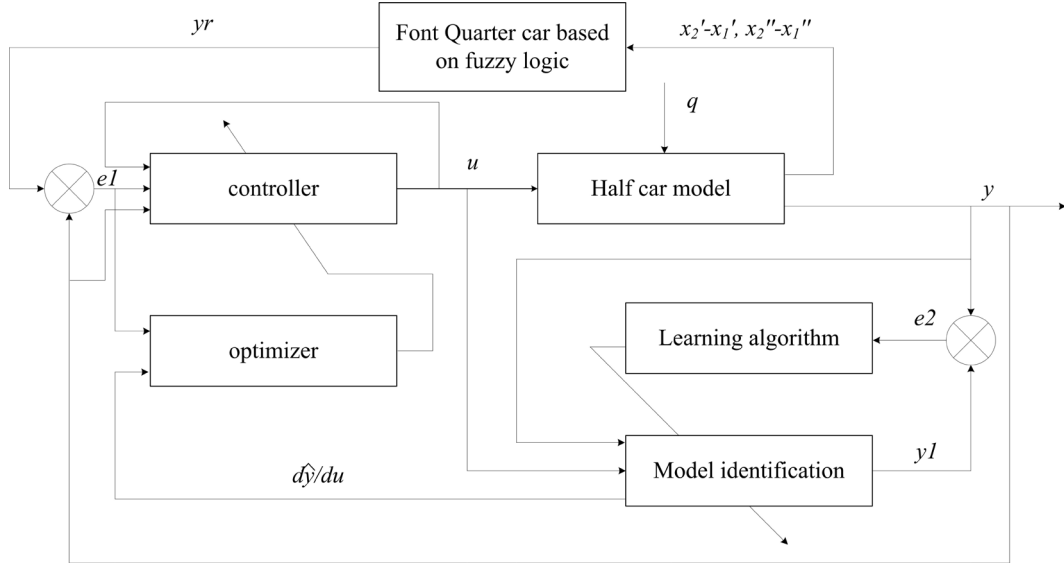


Figure 3: Control strategy of the whole system and the control flow process

The control system includes the half vehicle model, fuzzy controlled reference model, model identification part and the neural network optimizer. The reference model is the front quarter car model which is based on fuzzy logic, then the movement of the front wheel can be regarded as the reference signal followed by the rear suspension system. The type of fuzzy inference system is Mamdani. The velocity and acceleration of the front spring mass will be the input of fuzzy system. Due to the nonlinear characteristics of the air bag, the numerical calculation cannot derive a precise relationship between the road input and the suspension output. So the neural network identification will help to online identify the response and the input of the suspension system and provide the basis for the optimizer and the neural controller. The structure of the neural network controller is 4-22-1 type. The input layer is defined as below,

$$O_i^{(1)}(k) = \begin{cases} y(k-i) \\ u(k-i+n+1) \end{cases} \quad (9)$$

The hidden layer is designed as,

$$\begin{cases} n_i(k) = W_{ij}^{(1)} O_i^{(1)}(k) + B_i^{(2)} \\ O_i^{(2)} = 1 / \{1 + \exp[-n_i(k)]\} \end{cases} \quad (10)$$

where $W_{ij}^{(1)}$ stands for the weights of the hidden layer and $B_{ij}^{(2)}$ stand for the threshold of the neurons of the hidden layer. And the output layer is designed as,

$$\hat{y}(k+1) = \sum_i W_i^o O_i^{(2)}(k) + B^{(3)} \quad (11)$$

and $\hat{y}$, $W_i^{(o)}$ and $B^{(3)}$ stands for the neural network output, hidden layer weights and the output threshold, respectively.

As to the neural network controller, the structure adopts the 4-15-1BP neural network type. With the aid of model identification, the relationship between half car model input u and output y can be achieved by neural network, which can be replaced by $d\hat{y}/du$. Therefore, the neural network controller can be updated according to the difference e_1 between reference output y^r and real suspension output y and $d\hat{y}/du$. At the same time, the index performance can be regarded as,

$$E = [y_r(k+1) - y(k+1)]^2 / 2 \quad (12)$$

where $y_r(k+1)$ represents the reference model output.

4. Simulated Results

Using parameter tabulated in Tables 1 to 2, the numerical results can be simulated using Matlab/Simulink, while the road input is defined as a step input in (13):

$$Z_{0f} = \begin{cases} 0 & 0 < t < 1 \\ 0.03 & t \geq 1 \end{cases} \quad (13)$$

Table 1: Parameter of air bag

<i>Parameters</i>	<i>Meaning</i>	<i>Unit</i>	<i>Value</i>
A_{0f}	initial effective area of front air spring	m^2	0.0381
A_{0r}	initial effective area of rear air spring	m^2	0.0706
α_f	change rate of effective volume of front air spring	-	0.059
α_r	change rate of effective volume of rear air spring	-	0.0827
β_f	change rate of effective area of front air spring	-	0.0186
β_r	change rate of effective area of rear air spring	-	0.0207
V_{0f}	initial effective volume of front air spring	m^3	0.0078
V_{0r}	initial effective volume of rear air spring	m^3	0.0233
p_{0f}	air pressure of initial state of front air spring	Mpa	0.382
p_{0r}	air pressure of initial state of rear air spring	Mpa	0.3
p_a	standard atmospheric pressure	Mpa	0.1
γ	standard atmospheric pressure	-	1.33

Table 2: Parameters for EV

Parameter	Value
v	20m/s
M	1000kg
I	3800kgm ²
m_{1f}	90kg
m_{1r}	100kg
C_{sf}	3500Ns/m
C_{sr}	3500Ns/m
K_{tf}	192000kN/m
K_{tr}	192000kN/m
L_a	1400mm
L_b	1380mm

Fig. 4 illustrates the performance of NN controller for EV. The upper figure is the active force uttered by an NN controlled hydraulic damper and the lower figure is the plant response for NN MRC. The more accurate the neural network output and the reference model output, the better control performance can be achieved.

Fig. 5 shows the results of rear sprung mass acceleration based on the comparison between different control strategies for front suspension. Obviously, the fuzzy controller which is based on the empirical knowledge can provide a better performance of front sprung mass acceleration. Therefore, the rear sprung mass acceleration can be approved according to the front one.

Fig. 6 shows the comparison of sprung mass accelerations between fuzzy logic based MRC and PID based MRC. Due to the different weight distribution between ICEV and EV, a comparison of sprung mass accelerations for both ICEV and EV air suspension system is conducted in Fig. 6. Fig. 7 shows the control performance of the fuzzy logic based MRC from normal PID controller.

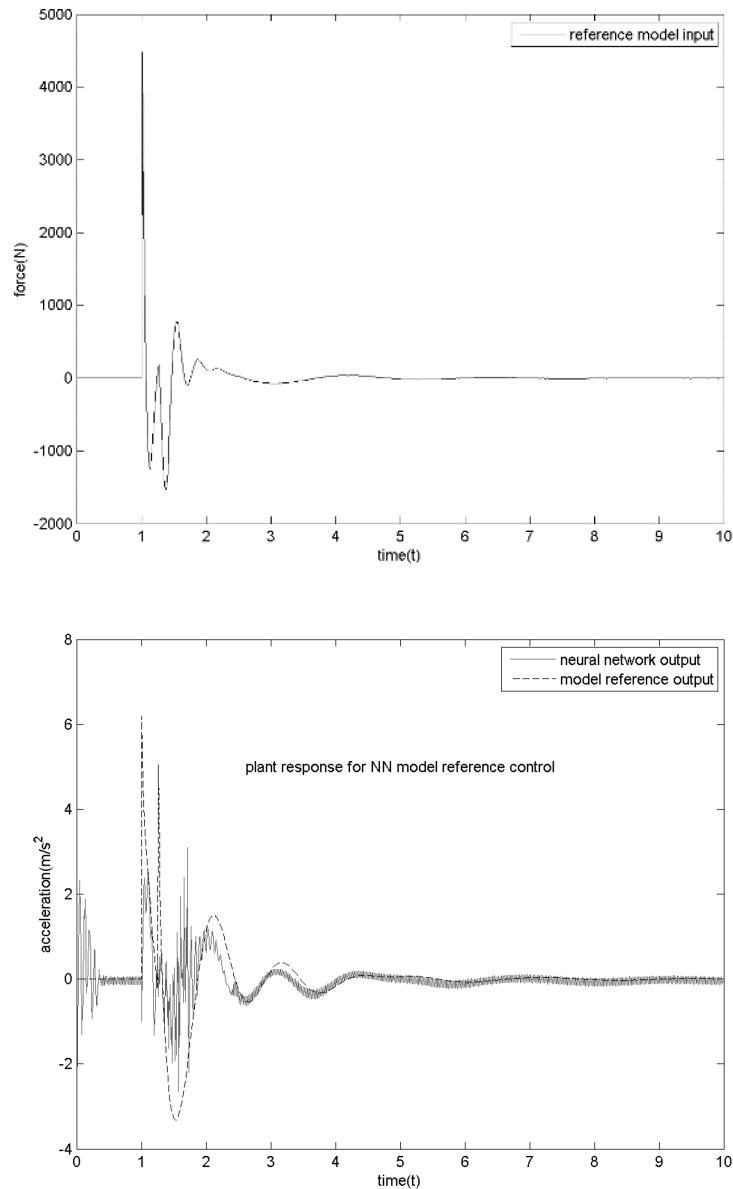


Figure 4: Plant response of NN MRC for EV

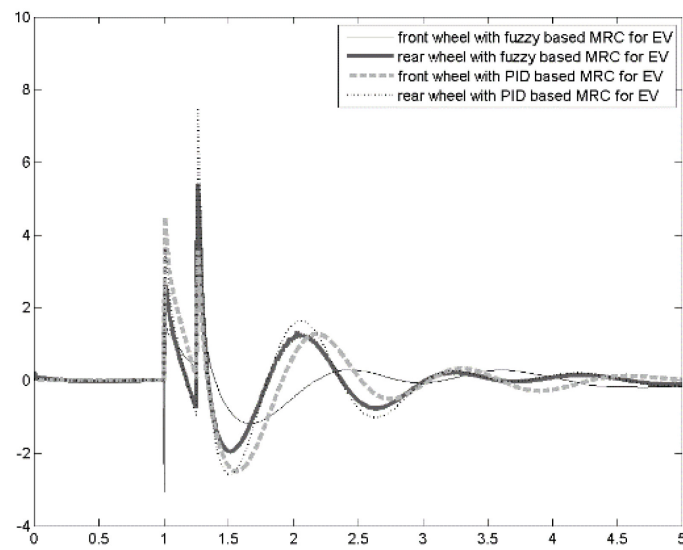


Figure 5: Comparison between fuzzy logic based MRC and PID based MRC for EV

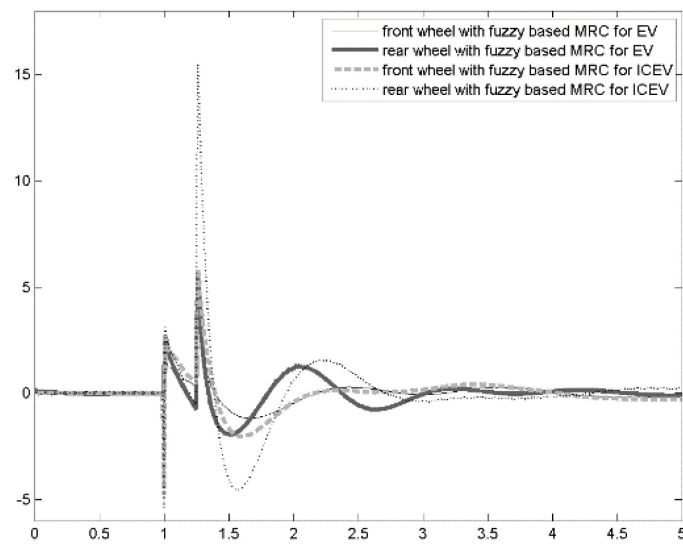


Figure 6: Comparison of sprung mass acceleration between EV and ICEV

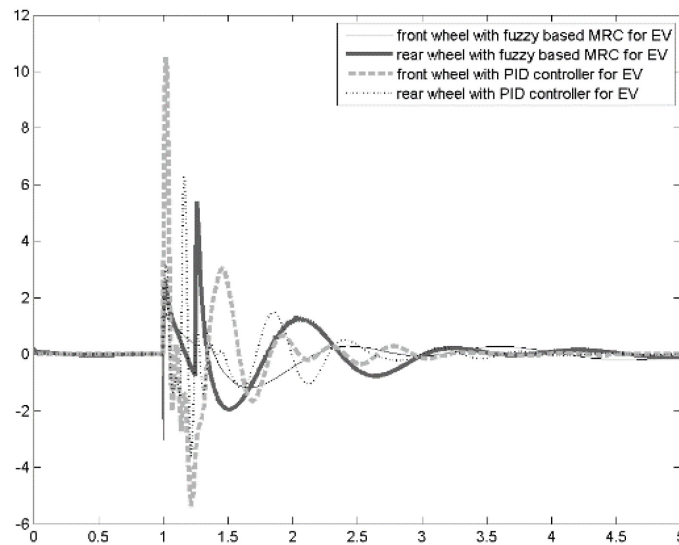


Figure 7: Comparison of sprung mass accelerations between MRC and PID control

5. Summary

This paper introduced a new control method which is integrated with fuzzy logic and neural networks particularly suitable for EV suspensions. By comparing different control strategies for front suspension in EV, the fuzzy logic based NN MRC method can provide a better ride quality. At the same time, by comparing different control strategy applied on EV Air suspension system, simulation results indicated that the proposed fuzzy logic based MRC is superior to PID controller. Besides, weight distribution itself plays an important role for the MRC. Therefore, EV which is of an even weight distribution is more suitable for this control method. However, the structure of the NN consumed more computer simulation time. So a new time saving regression method can be further investigated in the future works.

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Authors



Shaojia Huang was an MSc student of the University of Macau. Now she is a teaching assistant of Jilin University Zhuhai College. Her research interests include lambda control of combustion engine and automotive electronic technology.



Dr. T.W. Ching is currently an Assistant Professor of the University of Macau. His research interests include clean energy and environment, engineering economics, power electronic converters, variable speed drives, electric vehicles and charging infrastructure. He is a Chartered Engineer, Member of the IET, Member of the CIBSE, and Member of the HKIE.



Dr. Wenlong Li received the BEng degree from Sichuan University in 2005, the MEng degree from University of Science and Technology of China in 2008, and PhD degree from the University of Hong Kong in 2012, respectively. Currently, he is with the University of Hong Kong. His research interests are the areas of electric drives, electric vehicles and renewable energy harvesting.



Luwei Zeng received the BEng in Mechanical Engineering from Durham University and is currently an MSc student of the University of Macau. Her research interests are focused in electric vehicle technologies.



Prof. K.T. Chau is with the Dept. of Electrical and Electronic Engineering and Director of International Research Centre for Electric Vehicles at the University of Hong Kong. His research interests are electric vehicle technologies, renewable energy systems, machines and drives, power electronics. In these area, he has published 5 books, 8 book chapters and over 250 refereed journal papers as well as many conference papers and industrial reports. Prof. Chau is a Chartered Engineer, Fellow of the IET, and Fellow of the HKIE. He is elected Fellow of the IEEE for Contributions to Energy Systems for Electric and Hybrid Vehicles.



Prof. C.C. Chan is currently an Honorary Professor at the University of Hong Kong. He has authored 11 books, published over 300 technical papers, and holds 10 patents. Prof. Chan is a Fellow of the Royal Academy of Engineering, U.K., IEEE, IET and HKIE. He is also an Academician of Chinese Academy of Engineering and Ukraine Academy of Engineering.