A Fuzzy Logic-Based Energy Management Strategy for Optimal Solar Car Performance

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Abstract

This paper presents the development of an intelligent energy management system for a competitive solar vehicle, designed to optimize race performance by emulating the decision-making processes of an expert strategist. We have designed and implemented a Mamdani-type fuzzy inference system that translates seven critical real-time inputs—including battery state of charge, solar irradiance, and vehicle dynamics—into a recommended optimal speed. The core of this work is the systematization of heuristic driving knowledge into a robust, rule-based engine. The system's logic was further refined to handle suboptimal operating conditions, such as periods of inefficient motor performance. Validation was conducted through extensive simulations across various race scenarios, with the engine's outputs consistently aligning with the strategic choices of the team's experienced strategists, thereby confirming its legitimacy and effectiveness as a tool for competitive solar racing.

1. Introduction

Energy obtained from nonrenewable resources can be costly, unavailable or poorly distributed, and harmful for environment in lots of ways. All these circumstances direct to utilize renewable energy resources such as solar, wind, and geothermal energy. Between 2005 and 2015, production of renewable energy in European Union raised by 71.0 % in general and renewables have 13.0 % portion of the EU-28's gross inland consumption [1]. Additionally, usability of these resources enlarge in electricity generation, heating, and transportation sectors [2]. Besides, demand on sustainable and efficient solution in transportation causes renewable energy usage to come into a prominence. While renewable energy sources had 1.8 % the average share in transport fuel consumption in 2005, this proportion rise to 3.7 times and became 6.7 % in 2015 [1]. In transportation, solar power can be an effective alternative for providing energy.

Istanbul Technical University Solar Car Team (ITU SCT) was founded in 2004. The team purposes design of effective solar electric vehicles and spreading the solar mobility concept and renewable energy usage. This team also built 8 cars, one of which is a 4-seated family car. Their 9th car is on process with the aim of racing in one of the most significant solar car event World Solar Challenge (WSC). Participants have to complete t the 3021 km-route from Darwin to Adelaide with solar energy (Fig. 1). The goal for the event is travelling at the highest average speed.

There are several matters that should be improved in order to be the winner team in the WSC. First of all, a successful design that can achieve minimum aerodynamic drag and lighter mass is very critical. Moreover, selection of electric motor and solar array can enhance the efficiency of the solar car. Accurate estimation of battery state of charge is also said to be as another essential. On the other hand, a correctly applied race strategy handle all solar car characteristic with external factors like slope of the road and weather conditions.

Fig. 1. 3,000 km route of World Solar Challenge

Plenty of researches indicate that accurate energy management of a solar car is a crucial application in order to win the race. In an earlier research, strategy of the winner team of WSC 1999 Aurora Solar Car Team is determined [3]. Another study presented by Solar Car team Twente for WSC [4]. Therefore, Hamiltonian optimization theory is used to determine the critical velocity of the solar car that varies with the solar power [5]. Besides, Big Bang – Big Crunch optimization method is developed for the energy management of the ITU Solar Car ARIBA 5 that competed in WSC 2013 [6]. Besides, University of

Illinois conducted a study about improving the strategy for Sunrayce 95 [7].

In this study, a fuzzy based intelligent strategy engine for 9th car of ITU Solar Car Team B.O.W. ISTKA is created. Mamdani type inference is preferred in order to implement the structure. The engine gets several inputs that influence the overall performance of the solar car and gives speed change as an output.

The paper organized as follows. In Section 2, specification for the solar car B.O.W. ISTKA is given. Section 3 includes detailed explanation of fuzzy based engine. Moreover, fuzzy based decision-making system is manipulated for inefficient motor operation in Section 4. Section 5 is also for testing the structure. Section 6 is conclusion.

2. Specifications of the Solar Car

General properties of the solar car B.O.W. ISTKA is given in Table 1. In mechanically, the design of the solar vehicle should be improved in terms of aerodynamic losses. For this reason, the solar vehicle is designed as asymmetric catamaran.

This solar car has an axial flux permanent magnet motor that located in the rear left wheel of the car. Motor and motor driver efficiency is %98.

Monocrystalline silicon is the based material for solar cells. The area of the solar cell on the car is limited to 4 m^2 by WSC organization. Besides, solar cells have %25 of efficiency in order to power generation from sun.

Also, lithium polymer battery pack is utilized in the solar vehicle. The energy density per kilogram for lithium polymer type battery is greater than other ones. All components considered, the overall efficiency of the B.O.W. ISTKA is calculated as %82.

Table 1. Features of the B.O.W. ISTKA

Features of the B.O.W. ISTKA	
Production year	2017
Mass (kg)	159
Size (m)	4x1.8x1.1
Motor type	Axial flux permanent magnet motor
Solar cell type	Monocrystalline silicon
Battery type	Lithium Polymer
Vehicle body	Carbon-fiber
Aerodynamic Drag Coefficient	0.1
Rolling Resistance Coefficient	0.0035

3. Structure of the Fuzzy Based Strategy Engine

Fuzzy logic is actually a multi-valued logic system that can be applied in case of the excessive system complexity and nonlinearity. It introduced by Lotfi Zadeh in order to explain fuzzy-based decision making and some algorithm of complex system [8]. After then, Ebrahim Mamdani presented the concept of first fuzzy control [9].

During this study, Mamdani inference mechanism is used. The inference system for Mamdani can be described as a process whose output membership functions are fuzzy sets. Advantage of this type of fuzzy modelling is opportunity for transferring the knowledge of the operator to the model. Fuzzy based structure also uses product as 'AND' operation and center of gravity defuzzification method.

In this study, a fuzzy engine that determine the speed change of the solar car is designed step by step. This decision making system is based on the experience of the strategist in the team. Inputs of this engine affects the energy consumption of the solar car directly. Therefore, deciding process for the inputs is very substantial in terms of creating an effective fuzzy based energy management system. According to this perspective, components of the solar car and external factors should be reviewed carefully.

With respect to the discussions above, the strategy engine is formed with seven inputs. Inputs like spend energy, recovered energy, state of charge value, velocity, and solar irradiance has linguistic levels as SMALL (S), MEDIUM (M), and LARGE (S). The linguistic levels assigned to the input variable slope are POSITIVE (P), ZERO (Z), and NEGATIVE (N). Also, the system output has 5 membership functions with the linguistic levels like SO SLOW (SS), SLOW (S), CONSTANT (C), FAST (F), and SO FAST (SF). According to this inputs, the model includes 2187 scenarios.

The first input is the instant energy that is spend by the solar car. It is calculated by integrating multiplication of the bus bar current and voltage. Membership functions of spend energy (SE) is given in Fig. 2.

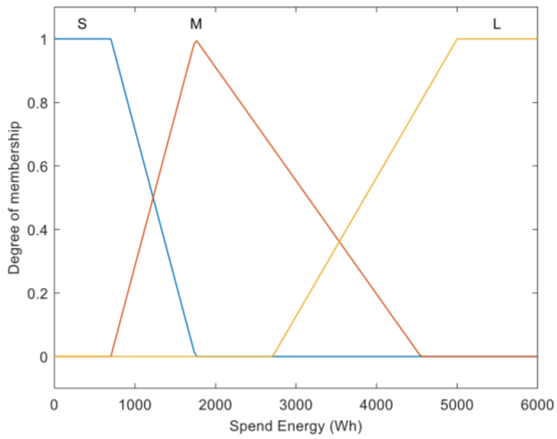

Fig. 2. Membership Functions of Spend Energy

The other input is chosen as battery state of charge. It is one of most essential parameter for decision-making algorithm. Knowledge of battery state of charge level is the part of rational energy management strategy. In Fig. 3., state of charge (SOC) membership functions can be examined.

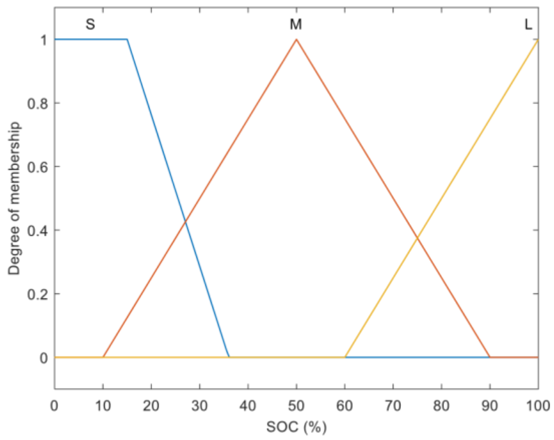

Fig. 3. Membership Functions of State of Charge

The third one is instant recovered energy that is the sum of the obtained solar energy and gained energy with the regenerative braking. Membership functions of recovered energy (RE) is in Fig. 4.

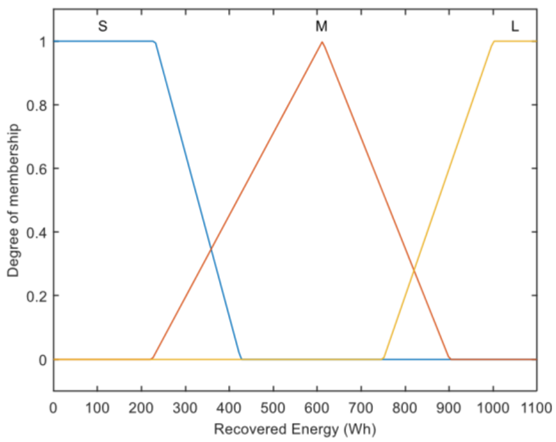

Fig. 4. Membership Functions of Recovered Energy

The next crucial input of the strategy engine instant velocity (V) of the solar car. The average velocity for the solar vehicle is desired as km/h because of the fact that membership functions of this input is defined as in Fig. 5.

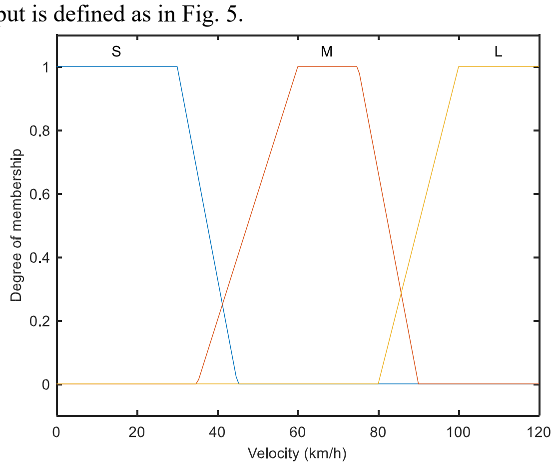

Fig. 5. Membership Functions of Velocity

Another input that can impact the energy management strategy is remaining road (RR) to the target point. According to the WSC regulation, the start and end time of race for each day is 08.00 and 17.00. The membership functions of remaining road are specified considering average velocity, start time, and finish time of the race in Fig. 6.

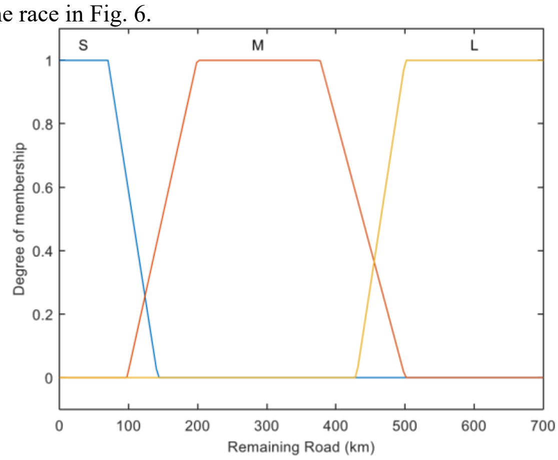

Fig. 6. Membership Functions of Remaining Road

Solar irradiance value is also influence the decision of speed changing. It can be defined as the output of light energy that measures at the Earth from the entire disk of the Sun [10]. Maximum solar energy that can be obtained is estimated between 0 and 1200 Wh. Therefore, the membership functions belong to solar irradiance (SI) is formed in Fig. 7.

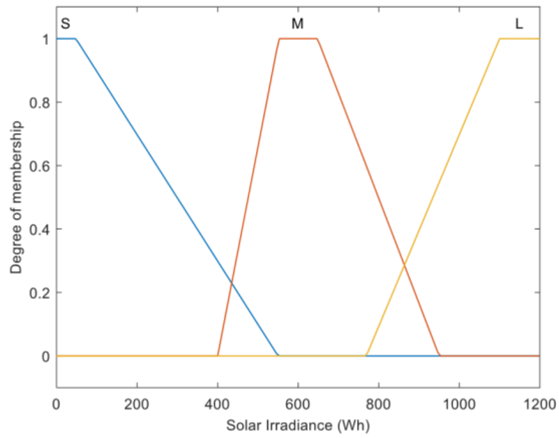

Fig. 7. Membership Functions of Solar Irradiance

The last input of the system is slope of the road. The slope has a huge impact on the current drawn by the motor. In Fig. 8, attitude over the race can be seen. It can easily be determined that there is no sharp increase in the attitude.

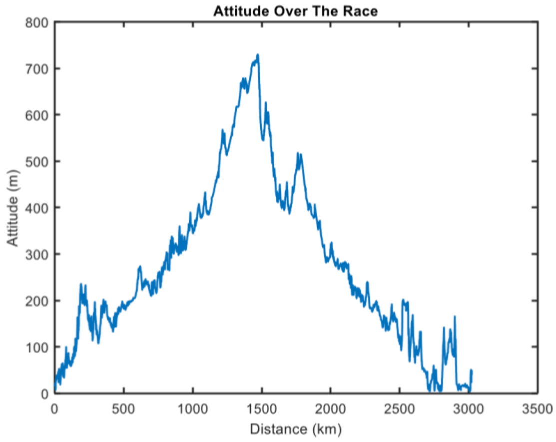

Fig. 8. Attitude Over The World Solar Challenge Path

So, the path that is driven by the solar car has an estimated slope (S) between -5 and 5 degree. Because of that, the membership functions of this input is determined as in Fig. 8.

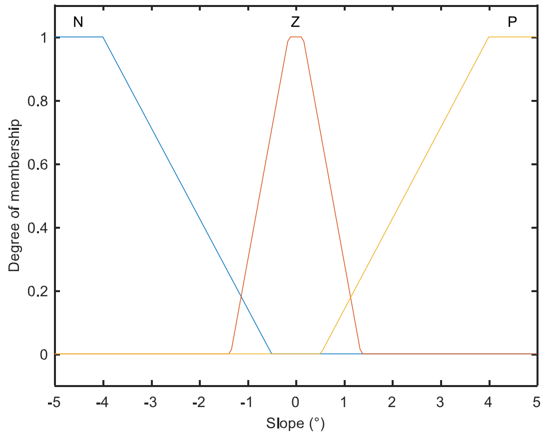

Fig. 8. Membership Functions of Slope

As mentioned before, output is the speed change of the vehicle. The membership functions of the output are given in Fig. 9.

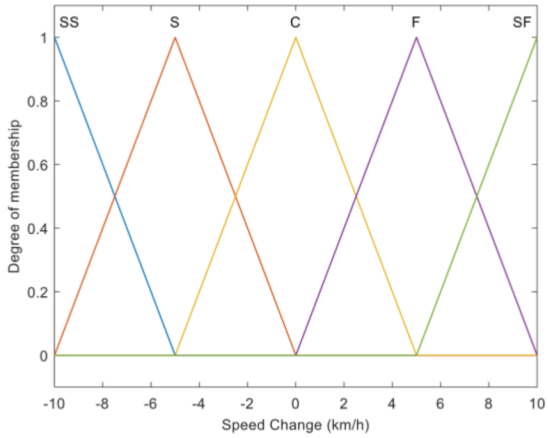

Fig. 9. Membership Functions of Speed Change

4. Structure of the Fuzzy Based Strategy Engine for Inefficient Motor

The fuzzy based structure is manipulated for the inefficient motor operation. Axial flux permanent magnet motor is chosen for B.O.W. ISTKA. It is presented as a surface mount motor kit that enables to build a brushless permanent magnet motor. The maximum winding temperature of this motor is 135 °C.

Therefore, it is advised that motor should be powered of when the winding temperature is 110 °C [11]. The rise in winding temperature causes the decline in resistance of the thermistor. So, undesired temperature increase can worsen the overall efficiency of the motor.

Under above matters, the race strategy of the solar car has to change in order to greater motor temperature. So, membership functions of the one input and output of the strategy engine are modified. This input is the velocity of the solar car. The maximum velocity of the solar vehicle is restricted to 80 km/h when the winding temperature is higher than 90 °C. Hence, the membership functions for the velocity input are altered and shown in Fig. 10.

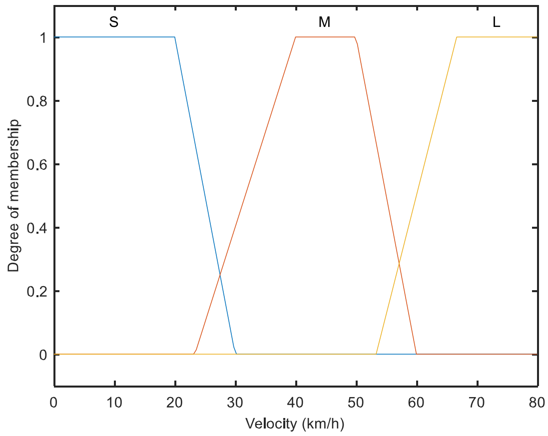

Fig. 10. Modified Membership Functions of Velocity

In addition, change in the velocity should be limited. For this purpose, speed change is kept between +5 and 5 km/h. The membership functions of the output are given in Fig. 9.

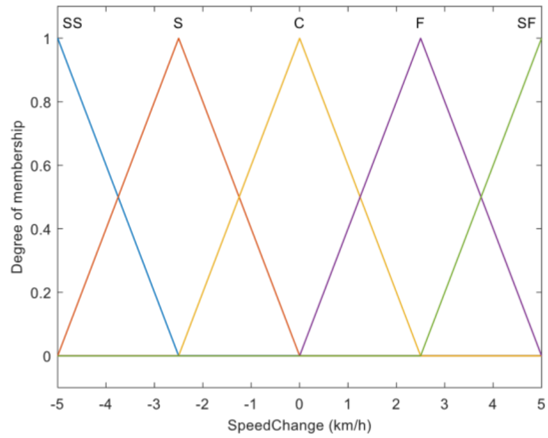

Fig. 11. Modified Membership Functions of Speed Change

5. Testing of the Strategy Engine

Decision-making system should be tested in order to evaluate the performance and reliability. These tested should also be repeated for both efficient and inefficient motor operations. The system has to give a response that fits the optimal driving strategy determined by the strategists of the team. Therefore, several cases are formed in Table 2. Outputs of these cases are given in below.

- **Case 1 for Efficient Motor Operation:** After the start time, the solar car should speed up in case of owning unsatisfied velocity. Suggested speed change is +3.38 km/h. **Case 1 for Inefficient Motor Operation:** After the start time, the solar car should travel with a constant speed even if it has unsatisfied velocity: Suggested speed change is 1.10 $x10^{-16}$ km/h.

- **Case 2 for Efficient Motor Operation:** In a fine situation, the car should travel with a constant velocity.
  Suggested speed change is -1.47x10^{-16} km/h. **Case 2 for Inefficient Motor Operation:** Even in a fine situation, the car should not accelerate. Suggested speed change is -7.36x10^{-17} km/h.

- **Case 3 for Efficient Motor Operation:** In case of being near to the daily target point, the car should slow down because of the worse system inputs.
  Suggested speed change is -5 km/h. **Case 3 for Inefficient Motor Operation:** In case of being near to the daily target point, the car should slow down because of the worse system inputs. However, the negative acceleration should be lower than before.
  Suggested speed change is -2.5 km/h.

- **Case 4 for Efficient Motor Operation:** Even in worse situation, speeding up is needed for low speeds:
  Suggested speed change is 1.72 km/h. **Case 4 for Inefficient Motor Operation:** In worse situation, solar car that travels with low speeds should not accelerate.
  Suggested speed change is 4.01x10^{-17} km/h.

- **Case 5 for Efficient Motor Operation:** Even in a great situation, some velocity limits should not be exceeded. (Velocity of the car is 110 km/h for this case.)
  Suggested speed change is -9.36x10^{-17} km/h.
  Case 5 for Inefficient Motor Operation: Even in a great situation, the velocity limit should not be exceeded. This limit is lower for inefficient motor operation. (Velocity of the car is 80 km/h for this case.)
  Suggested speed change is -4.68x10^{-17} km/h.

- **Case 6 for Efficient Motor Operation:** The fuzzy based strategy engine should suggest lower speeds in worst cases.
  Suggested speed change is -1.69x10^{-16} km/h.
  Case 6 for Inefficient Motor Operation: The fuzzy based system should also suggest lower speeds in worst cases for inefficient motor operation.
  Suggested speed change is -8.47x10^{-17} km/h.

- **Case 7 for Efficient Motor Operation:** At the end of the day, the driver speeds up unnecessarily. So, slowing down should be offered by the engine.
  Suggested speed change is -2.31 km/h. **Case 7 for Inefficient Motor Operation:** At the end of the day, the driver speeds up unnecessarily. So, slowing down should be offered by the engine.
  However, change in the speed should be less. Suggested speed change is -1.44 km/h.

Table 2. Cases for Testing the Fuzzy Based Strategy Engine

	SE (Wh)	SOC (%)	RE (Wh)	V (km/h)	RR (km)	SI (Wh)	S (°)
1	1000	100	0	70	300	1100	0
2	5000	50	1000	80	150	880	0.1
3	10	10	500	75	150	650	0
4	750	70	1000	60	300	800	0.2
5	5500	90	1000	80/110	20	1000	-1
6	5000	10	300	20	600	300	1.5
7	1000	50	0	80	350	850	0.1

6. Conclusions

Uncharted territory of control and modelling field fuzzy based driving strategy engine is implemented in this study. The system is designed considering the newest solar car of ITU Solar Car Team B.O.W. ISTKA. The engine has seven inputs and gives one output as vehicle speed change. For considering different type of case, system contains 2187 situation that can be met in race.

This structure is also manipulated for inefficient motor operation. Inefficient motor operation is defined as higher motor temperature. Memberships functions of velocity and speed change is altered in order to describe this undesirable condition.

Fuzzy based decision making engine is tested for 7 cases that may be encountered during the race. The results of these tests show that the engine suggest with the strategist collaterally. After verification process, it is obvious that the suggestions from the intelligent structure present an optimal driving strategy for a solar car in WSC.

7. References

[1] Zadeh, L.A., 1996, Fuzzy logic = computing with words, IEEE Transactions on Fuzzy Systems, Vol. 4, No. 2, pp. 103-111.

[2] Mendel, J.M., 2001, Uncertain Rule-Based Fuzzy Logic Systems: Introduction and New Directions, Prentice Hall, Upper Saddle River, NJ, USA.

[3] Howlett, P., and Pudney, P., 1995, Energy-Efficient Train Control, Springer, London.

[4] Serway, R.A., and Jewett, J.W., 2013, Physics for Scientists and Engineers with Modern Physics, 9th Edition, Cengage Learning.

[5] U.S. Energy Information Administration (EIA). 2016. Annual Energy Outlook 2016. [ONLINE] Available at: https://www.eia.gov/outlooks/aeo/archive/2016/. [Accessed 10 October 2016].

[6] Ab-Rub, H., Iqbal, A., and Husain, I., 2012, Modeling and Control of a Solar-Powered Vehicle. 2012 IEEE Transportation Electrification Conference and Expo (ITEC), Dearborn, MI, USA.

[7] Baumann, J., et al., 2000, Energy management strategies for a fuel cell/battery hybrid powertrain, SAE Technical Paper 2000-01-1049.

[8] Gillespie, T.D., 1992, Fundamentals of Vehicle Dynamics, Society of Automotive Engineers (SAE), Warrendale, PA, USA.

[9] Pudney, P., and Howlett, P., 2002, Critical Speed of a Solar Car, Optimization and Engineering, Vol. 3, pp. 97-107.

[10] Sciarretta, A., and Guzzella, L., 2007, Control of Hybrid Electric Vehicles, IEEE Control Systems Magazine, Vol. 27, No. 2, pp. 60-70.

[11] Boveri, M., et al., 2001, Optimization of Energy Management in a Solar Car. World Solar Challenge Conference.

[12] Lee, C.C., 1990, Fuzzy Logic in Control Systems: Fuzzy Logic Controller, Part I & II, IEEE Transactions on Systems, Man, and Cybernetics, Vol. 20, No. 2, pp. 404-435.

[13] Corno, M., et al., 2011, A driving strategy for solar-powered vehicles based on online optimization, IEEE Transactions on Control Systems Technology, Vol. 19, No. 5, pp. 1056-1067.

[14] Schouten, N.J., et al., 2003, Fuzzy logic control for parallel hybrid vehicles, IEEE Transactions on Control Systems Technology, Vol. 11, No. 3, pp. 460-468.

[15] Larminie, J., and Lowry, J., 2012, Electric Vehicle Technology Explained, 2nd Edition, John Wiley & Sons, Ltd.

[16] Hissel, D., et al., 2010, A review of fault-tolerant control systems for PEM fuel cell applications, IEEE Transactions on Industrial Electronics, Vol. 57, No. 6, pp. 1917-1925.

[17] American Solar Challenge. 2016. Regulations. [ONLINE] Available at: https://americansolarchallenge.org/the-competition/2016-regulations/. [Accessed 15 September 2016].

[18] Darshan Bhavesh Mehta . "Ergonomics of a Custom Made Solar Electric Road Vehicle". International Journal of Engineering Trends and Applications (IJETA) V3(4): Page(29-33) Jul - Aug 2016.

[19] Onori, S., Serrao, L., and Rizzoni, G., 2016, A review of hybrid electric vehicle energy management strategies, Annual Reviews in Control, Vol. 41, pp. 277-293.

[20] Salmasi, F.R., 2007, Control Strategies for Hybrid Electric Vehicles: A Review, IEEE Transactions on Vehicular Technology, Vol. 56, No. 5, pp. 2393-2404.

[21] El-Sharkh, M.Y., and Rahman, A., 2004, Fuzzy logic control of a solar-powered vehicle, Renewable Energy, Vol. 29, No. 12, pp. 1969-1981.

[22] Takagi, T., and Sugeno, M., 1985, Fuzzy identification of systems and its applications to modeling and control, IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-15, No. 1, pp. 116-132.

[23] Milliken, W.F., and Milliken, D.L., 1995, Race Car Vehicle Dynamics, Society of Automotive Engineers (SAE), Warrendale, PA, USA.

[24] Pansino, M., and Frank, A.A., 1995, A Fuzzy Logic Controller for Hybrid Vehicle Power Management. Proceedings of the 1995 American Control Conference, Seattle, WA, USA, pp. 1198-1202.