J Inno Sci Eng 2018, 2(1): 1-7

A Brief Review on Fuzzy Logic Used in Vehicle Dynamics Control

Erdem Uzunsoy

Bursa Technical University, Faculty of Engineering and Natural Sciences, Department of Mechanical Engineering, Automotive Engineering Subdivision, 16310 Bursa, Turkey

Abstract

As an implication of a mathematical set theory, fuzzy logic has widely been used in engineering applications, since its invention. One of the popular areas, which the logic could successfully penetrate the real world, is the automotive engineering. Especially; rulemaking authorities, a competitive sector and more conscious customers challenge the vehicle designers to use state of the art technologies for better performance, safety and higher dynamic requirements. Therefore, although the style design has been an attraction point in the first place, nowadays, control systems have been the distinguishing parameter of the vehicle design. Certainly, not only the hardware used for the control, but also the method used is important in judgement of the system's success. Fuzzy logic control (FLC) has been studied and applied in vehicle dynamics control model and the systems for decades. The method is classified in the intelligent control systems and is capable of dealing with the systems consisting of uncertainty and non-linearity as in some fields of automotive engineering. From this point of view, this paper aims to reveal the most commonly used FLC applications in vehicle dynamics literature.

Keywords: Fuzzy logic, Vehicle dynamics control, Automotive engineering

1. Introduction

Fuzzy set theory was first presented by Lotfi Aliasker Zadeh in his famous study, "Fuzzy Sets" [1]. Although it had been seen as a mathematical entertainment in the early days of its presentation, it has found a great variety of application area in time, ranging from control engineering, machine intelligence, pattern recognition, qualitative modelling, signal processing, information processing, decision making, management, medicine, finance, motor industry, robotics, and so on [2].According to its inventor [1] a fuzzy set can be defined as a class of objects with a continuum of grades of membership. For an element in a universe that contains fuzzy sets, unlike the classical or crisp sets, transition can be gradual [3].

Zadeh improved his work on the theory of possibility into a formal mathematical logic system and introduced a new concept by applying natural language terms. The new logic for representing and manipulating fuzzy terms was called fuzzy logic. Fuzzy logic, as a term, means a pre-orderly identified logic in a set [4]. The main purpose of the logic is to form the theoretical foundation for reasoning about imprecision; such reasoning has been referred to as approximate reasoning [3]. Almost after a decade of the invention,a method was proposed by Mamdani [5], as a first attempt of fuzzy logic to control a steam engine and boiler combination by developing a set of linguistic control rules provided by the experienced human operators. The fuzzy logic control (FLC) approach is based on experience and the system control inputs are the result of a linguistic process. Mamdani-type fuzzy inference system (FIS) is preferable in FLC instead of Takagi–Sugeno (TS) type FIS, due to its rule structure, which depends on the natural IF-THEN rules. Developing the fuzzy rules are more intuitive so that the parameters can be determined later using some optimisation techniques such as genetic algorithm and particle swarm optimisation [6]. Ever since Mamdani developed his method, it has been the most commonly used FIS and the literature on the area has grown rapidly [7].

Among different computational intelligence methods such as evolutionary computing, neural networks etc., the fuzzy logic can be of special relevance for intelligent automotive systems, due to its good applicability for identification tasks and preview control under the presence of enough data and model

*Corresponding author: Tel: +90.224.3003536 E-mail: erdem.uzunsoy@btu.edu.tr
Received 07 November 2017; Accepted 5 June 2018

uncertainty [8]. As discussed by Furukawa [9], fuzzy logic can describe the systems in a linguistic way and especially its nature is well suited to the subjective problems as it occurs in vehicle dynamics and it presents a proper method in controlling the nonlinear systems with an acceptable performance.

The large amount of the fuzzy rules, on the other hand, can make the analysis, highly complex. Therefore, a hybrid fuzzy control design method based on the sliding-mode control (SMC) scheme has been proposed by some researchers. The method in its most general form is referred to as fuzzy sliding-mode control (FSMC) design methods [10]. FSMC requires fewer fuzzy rules than the conventional FLC approach, due to the single variable used in defining the fuzzy input. Although FLC and FSMC like methods are both effective, their major disadvantage is that the FIS should be tuned by time-consuming basic trial and error procedures. To tackle this problem, some optimisation methods and adaptive fuzzy control (AFC) based on the Lyapunov synthesis approach has been extensively studied [10]. This paper, on the other hand, aims to represent the most commonly used fuzzy logic control applications on vehicle dynamics, rather than focusing on the improvement on the fuzzy set theory.

2. Driver modelling

A complete vehicle dynamics and a driver model is crucial for the simulation of many different scenarios in vehicle dynamics analysis, due to the mathematical models used to estimate the performance of the proposed control systems are highly cost effective [6]. However, strict mathematical functions, sometimes, may be restrictive for the real-world behaviour of the vehicle, in determination of vehicle dynamics properties. Therefore, for the purposes of assessing the driveability, manoeuvrability and safety of the vehicles, it may be more realistic and a good practice representing the behaviour of the human driver in the vehicle models. The fuzzy logic has proven to be an effective tool for handling imprecision and uncertainty, which are both important characteristics of driving environments and it can take into account the vague human assessments [11].

For a nonlinear vehicle dynamics problem, a fuzzy logic controller can represent driver behaviour by offering the ability to develop rules which make intuitive sense [12].The fuzzy methods in driver modelling originated from the fuzzy set theory has been studied since 1980s [8]. However, as discussed by Ivanov [8], the first fuzzy models of the human reasoning for more complex driving situations could be developed by Kageyama, after a decade. Kageyama has introduced a model that converts the visual information into a perceived risk level within a fuzzy control model [13]. Angular velocity of the steering wheel was applied as the driver’s steering input by considering the risk level and its rate at a certain visible object ahead by applying fuzzy control. A steering torque were derived as the lateral control input of the vehicle, using the information of actual steering angle and desired steering angular velocity [14].

Hessburg and Tomizuka [15, 16] developed a fuzzy driver for vehicle lateral control on a test vehicle. The controller included a feedback module to determine the control action from state errors, a preview module for preview information regarding upcoming road curvature and a gain scheduling module to handle the effects of the vehicle velocity. Their rule development for fuzzy modelling was based on engineering judgement and observed human driving characteristics. Preview information has become the most important part of the human driver modelling. Uzunsoy and Olatunbosun [17] developed a model which introduced “secondary target” concept, as a human eye feedback, into the literature. Uzunsoy improved his concept and explained in more detail with his recent study [6]. In the study, by considering a human driver’s real driving behaviour, “secondary target” approach was matched with the “peripheral vision” concept, which is a part of vision that occurs outside the centre of gaze. A human driver can detect the tendency but not gaze on it. Therefore, angular position and distance were used as the fuzzy perception inputs in mimicking human driver.

3. Antilock brake system

Antilock braking system (ABS) was introduced to be used in automobiles, in 1971 [18]. The purpose of antilock braking system is to avoid wheel locking and additional yaw moment due to the control action, thus maintaining the directional stability of the vehicle during braking. According to a study done by the Monash University, ABS has reduced the risk of multiple vehicle crashes by 18% and the risk of road departure crashes by 35% [19]. For an ABS system, the main control target is to keep the available friction coefficient as high as possible during braking, for the sake of providing the largest possible brake force, while avoiding the excessive wheel slip. Choosing a suitable control methodology is essential to get an effective response from the system for any vehicle dynamic system.

The most commonly applied control methods have been threshold, PID, sliding mode and intelligent control, since the invention of the system. The threshold method has been applied widely in the early stages of the system as a simple method by taking into account the up and down system pressure levels while the wheel acceleration and wheel slip are the control variables. PID control, on the other hand, is almost a general consensus on most of the control necessities, as it is only a matter of providing an efficient control. Sliding-mode control is a kind of robust control that provides an effective method to control the systems with nonlinear characteristics [20]. It consists of a sliding surface where a predefined function of error is zero, which models the desired closed-loop performance; and a control law, such that the system state trajectories are forced toward the sliding surface. Designing the sliding surface is of significant importance, as it determines the behaviour and performance of the control system. In general, an adaptive method based on least square optimisation must sample a sufficient set of new data points after each change of plant parameters before it can compute the poles and zeros of the new controllers. However, as a result of this requirement, a significant amount of additional delay occurs in the analysis due to several sampling periods each time a new control law is computed [21].For the ABS application, intelligent control, including fuzzy logic, genetic algorithms and neural networks, has been an emerging and effective solution to deal with the nonlinear, uncertain and varying dynamics of braking process. A fuzzy controller, for instance, can produce a response, immediately, once a new state has been detected. Mauer [21] represented the vehicle system in a straightforward motion with a single front wheel, simply as a quarter vehicle model including nonlinear behaviour of suspension system. The researcher studied the contradictory issues like dry pavement and black ice conditions. The designed fuzzy controller, in combination with decision logic to estimate the road condition, becomes an effective tool in providing braking torque control over operating conditions ranging from dry pavement to black ice. The controller's response was robust enough, and insensitive to internal noise, as well as to large noise amplitudes induced by rough road profiles.

Minh et al. [22] presented two ABS controllers for a real experimental setup in laboratory. They proposed a fuzzy and a PID controller for comparison. A detailed study of their performance after implementation on the ABS simulation model showed that FLC was superior to the PID controller from the performance point of view. FLC approach provided slip control with better convergence rates and there were not any observable overshoots. Besides, a better braking distance was achieved. Aksjonov et al. [23] proposed a multi-input, single-output FLC for an ABS, where both the slip and the vehicle velocity are considered as the inputs. Real time experiments were done using a quarter car test bench. The designed system aimed both the minimal slip ratio and the shortest braking distance to cancel the wheel blockage. The developed fuzzy algorithm could cope with the hardware and a consistency could be provided for different initial braking velocities. Tang et al. [24] proposed an adaptive fuzzy fractional-order sliding mode controller design method for ABS. The proposed method combined the fractional-order sliding mode controller and FLC. The FLC was designed to compensate the effects of parameters varying of ABS. Tuning of the controller was done in the light of Lyapunov based stability analysis. While there is a continuous research on ABS control for the sake of better performance and cost cutting, electric vehicle technology has been a new motivation for the development studies due to different necessities on some system elements.

4. Vehicle stability control systems (VSC)

VSC systems can be classified as direct yaw moment (DYC) based or as steering based [25]. The most successfully commercialised system depends on the DYC base and called Electronic Stability Control (ESP). Examples of the steering based systems are active (front) steering and four wheel steering (4WS). The ESP has a closed-loop algorithm designed to improve vehicle braking and handling response through programmed intervention in the braking system and/or drivetrain. The system uses the ABS and TCS base for the purpose, without the human intension. Recent literature, on the other hand, rather than examining a control method singularly, focuses on the integration of the methods aiming the similar purpose.

Jim at al. [26] introduced the rear wheel steer angle application to keep sideslip angle in an ideal range and then combined the additional yaw moment and rear wheel steer angle to improve the lateral movement stability. For the purpose, a fuzzy logic controller was designed and aimed to minimize deviation of the actual response to the expected value. Genetic algorithm optimization of the FLC of side-slip angle made the actual locus of the yaw rate closer to the ideal value. Boada et al. [27], on the other hand, integrated the front steering and just front wheel braking control by using FLC. A 3DOF vehicle model was used to estimate the sideslip angle and the real measurement of yaw rate obtained from a gyroscope sensor. Jianhua [28] proposed an integrated active front steering (AFS)/ESP system to improve vehicle handling and stability. A fuzzy logic control strategy was applied and effective results were obtained. Goodarzi and Alirezaie [29] designed an integrated fuzzy/optimal AFS/DYC controller. The system included five individual optimal LQR control strategies and a fuzzy blending logic also was utilized to manage each LQR control strategy contribution level in the final control action. As a result of the simulation, the advantages of the proposed control system over the individual AFS or DYC controllers were shown.

5. Vehicle Ride Comfort and Rollover Safety

Active or semi active suspension systems are used to control the vertical movement of the wheels to provide a smoother ride and/or comfort. Traditionally, the reference value for the vehicle body bounce and angular motions are assigned as absolute zero. This approach means compensating the change in the elevation of the vehicle by using the suspension travel/working space. If the tyre encounters a bump, the force actuator pulls the vehicle body down by losing the suspension travel as much as the bump height. If the tyre encounters a pothole, then the suspension travel is forced to elongate to reach the zero displacement in vehicle body motion [30].

Yagiz et al. [30] used FL in active suspension control. They applied a comparative analysis for a passenger seat, suspension system excluding the seat and the full system modes, to represent the effectiveness of the controller. The results pointed out the benefit of the seat suspension control as an addition to the main system control, with a trivial increase in cost.

Rao and Prahlad [31] have developed an active quarter-vehicle suspension system model to reduce the vertical acceleration by considering a reference model. The main motivation of the study was to demonstrate the application of FLCs in active suspension systems. The rule base of the FLC was depended on a developed look-up table. Bell-shaped fuzzy membership functions associated with the different linguistic variables were tuned by trial and error method to provide the intended sprung mass acceleration and deflection on parts. Barr and Ray [32] used a two degree of freedom quarter-vehicle suspension model to examine the design of their FLC. For the comparison purposes, a basic passive suspension and a Linear Quadratic Gaussian (LQG) controlled active suspension were also proposed to test the performance of the FLC. All the system models were subjected to the random linear power spectral density and white noise inputs. The FL controlled suspension model exhibited superior ride characteristics when compared to the LQG and passive suspension models. Besides, highly simplified rule base satisfied the target performance measures. Al-Holou et al. [33] proposed a robust intelligent nonlinear controller for active suspension systems. They used a combination of fuzzy logic, sliding mode and neural network methodologies and claimed a superior performance on conventional controllers. Gandhi [34] designed suspension system controllers on the base of PID, LQR, FL and Adaptive Neuro Fuzzy Inference System (ANFIS), using a 4

Degrees Of Freedom half-vehicle model in MATLAB-Simulink environment. The response of these controllers were analysed according to ISO 8608 standard against the passive suspension system. The ANFIS based controller performed better on the ‘peak over shoot’ and ‘settling time’ parameters of the road disturbances, when compared to the other controllers. Lian [35] presented an enhanced adaptive self-organizing fuzzy sliding mode controller to overcome the instability of active suspensions with a self-organizing fuzzy controller.

Recently, suspension control has also been used to prevent excessive roll, especially for the vehicles with higher centre of gravity. This kind of control method has been called as Active Roll Control (ARC). The method, on the other hand, is not obliged to use the suspension system. The similar response has been experienced by the application of direct yaw control, practically, ESP based system. Singh and Darus [36] proposed an ARC system, on the base of an active suspension system, having a feedback and feedforward FLC combination. The inputs to the feedforward FLC were the steering wheel angle and vehicle longitudinal velocity and the output of the feedforward FLC was the counter roll moment. For the feedback FLC, the roll angle error and error rate were the inputs whereas the counter roll moment was the output. The effectiveness of the control system was demonstrated by fishhook, step steer, and double lane change manoeuvres. Kadir et al. [37] aimed a roll moment rejection control of pneumatically actuated active roll control (ARC) suspension system for a passenger vehicle. While the inner loop of the FLC was aiming to protect the excessive load transfer, the outer loop tried to suppress both body roll angle and body vertical displacement. Kawashima [38] proposed a robust rolling stability control (RSC) based on ESP for Electric Vehicles (EV), with a distributed in-wheel-motor system. RSC was designed using two-degree-of-freedom control, which could track the reference value and had disturbance suppression capability. Due to the consistency problem of roll and yaw control, he composed ESP with an estimation algorithm and integrated a motion control system. A distribution ratio of roll and yaw control was determined based on rollover index (RI) which is calculated in ESP algorithm from rolling state information. The effectiveness of proposed methods was shown both by simulation and experimental results.

6. Conclusion

The paper addresses a brief survey on vehicle dynamics based applications of fuzzy control. It can be understood that fuzzy logic is highly promising on the most of the fields of vehicle dynamics. Especially, for the systems with uncertainty accompanying complex processes of vehicle dynamics, the logic depending on the experience is very effective. Certainly, this review study reflects very little essence from the field. Nowadays, commercially provided tools make the FLC applications on theoretical vehicle dynamics studies easier, however, sometimes, on the expense of reliability and objectivity. There is a strong need for examining the connection between the parameter settings and tuning of the fuzzy controller in terms of research studies in order to contribute to the current literature.

References

[1] Zadeh, L.A. (1965). Fuzzy Sets. *Information and Control*, 8: 338–353.

[2] Feng, G. (2006). A Survey on Analysis and Design of Model-Based Fuzzy Control Systems. *IEEE Transactions on Fuzzy Systems*, 14(5): 676-697.

[3] Ross, T.J. (2015). Fuzzy Logic –Fuzzy Logic with Engineering Applications, Wiley, West Sussex, UK, 3rd Edition, 585 p. ISBN: 978-0-470-74376-8.

[4] Trilaz, E., Ecioloza, L. (2015). Fuzzy Logic - An Introductory Course for Engineering Students, Springer, Switzerland, 1st Edition, 204 p. ISBN 978-3-319-14202-9.

[5] Mamdani, E. H., Assilian, S. (1975). An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller. *International Journal of Man-machine Studies*, 7: 1–13.

[6] Uzunsoy, E., Erkilic, V. (2016). Development of a Trajectory Following Vehicle Control Model. *Advances in Mechanical Engineering*, 8(5): 1–11.

[7] Dadios, E.P. (2012). Fuzzy Logic - Controls, Concepts, Theories and Applications. In Tech, Rijeka, Croatia, 1st Edition, 428 p. ISBN: 978-953-51-0396-7.

[8] Ivanov, V. (2015). A Review of Fuzzy Methods in Automotive Engineering Applications. European Transportation Research Review, 7:29.

[9] Furukawa, Y., Abe, M. (1997). Advanced Chassis Control Systems for Vehicle Handling and Active Safety. *Vehicle System Dynamics*, 28: 59-86.

[10] Aly, A.A., Zeidan, E.S., Hamed, A. Salem, F. (2011). An Antilock-Braking Systems (ABS) Control: A Technical Review. Intelligent Control and Automation, 2: 186-195.

[11] Ghaemi, S., Khanmohammadi, S., Tinati, M. (2010). Driver's Behavior Modeling Using Fuzzy Logic. Mathematical Problems in Engineering, vol. 2010, Article ID 172878.

[12] Plochl, M., Edelmann, J. (2007). Driver Models in Automobile Dynamics Application. *Vehicle System Dynamics*, 45:699–741.

[13] Pauwelussen J.P. (1999). Vehicle Performance, Swets&Zeitlinger, Lisse, The Netherlands, 1st Edition, 250 p. ISBN: 90 265 1542 1.

[14] Mastinu, G., Ploechl, M. (2014). Road and Off-Road Vehicle System Dynamics Handbook, CRC Press, NW, USA, 1st Edition, 1708 p. ISBN: 13:978-1-4200-0490-8.

[15] Hessburg T.,Tomizuka, M. (1994). Fuzzy Logic Control for Lateral Vehicle Guidance. IEEE Control Systems, 14: 55–63.

[16] Hessburg, T.,Tomizuka, M. (1995). Fuzzy Logic Control For Lane Change Maneuvers In Lateral Vehicle Guidance. California Partners for Advanced Transit and Highways (PATH). UC Berkeley: California Partners for Advanced Transportation Technology. Retrieved from: http://escholarship.org/uc/item/4zs9k1vx [Accessed 20 October 2017].

[17] Uzunsoy, E., Olatunbosun, O.A. (2003). A generic fuzzy pilot and path planning for vehicle handling dynamics simulation studies (SAE 2003 Transactions - journal of passenger cars: electronic and electrical systems, p.767. SAE paper 2003-01-2263, 2003.

[18] dos Santos, D., Cabral, E. (2008). A Novel Method for Controlling an ABS (Anti-lock Braking System) for Heavy Vehicle. SAE Technical Paper 2008-36-0039.

[19] Jalali, K., Uchida, T., McPhee, J., Lambert, S. (2012). Development of a Fuzzy Slip Control System for Electric Vehicles with In-wheel Motors. *SAE International Journal Alternative Powertrains*, 1(1):46-64.

[20] Ferro, J.,P., C. (2014). Design and Simulation of an ABS Control Scheme for a Formula Student Prototype. MSc Thesis, Tecnico Lisboa.

[21] Mauer, G., F. (1995). A Fuzzy Logic Controller for an ABS Braking System. *IEEE Transactions on Fuzzy Systems*, 3(4): 381-388.

[22] Minh, V., Oamen, G., Vassiljeva, K., Teder, L. (2016). Development of Anti-lock Braking System (ABS) for Vehicles Braking. *Open Engineering*, 6(1):554-559.

[23] Aksjonov, A., Vodovozov, V., Petlenkov, E. (2016). Design and Experimentation of Fuzzy Logic Controlfor an Anti-Lock Braking System. 15th Biennial Baltic Electronics Conference (BEC). Tallinn, Estonia on October 3-5, 2016.

[24] Tang, Y., Wang, Y., Han, M., Lian, Q. (2016). Adaptive Fuzzy Fractional-Order Sliding Mode Controller Design for Antilock Braking Systems. *ASME Journal of Dynamic Systems, Measurement and Control*, 138(4):041008 8p.

[25] Ding, N., Taheri, S. (2009). An adaptive integrated algorithm for active front steering and direct yaw moment control based on direct Lyapunov method. Information and Control. *Vehicle System Dynamics*, 48(10): 1193-1213.

[26] Jin, L., Xie, X., Shen, C., Wang, F., Wang, F., Ji, S., Guan, X., Xu, J. (2017). Study on Electronic Stability Program Control Strategy Based on the Fuzzy Logical and Genetic Optimization Method. *Advances in Mechanical Engineering*, 9(5): 1–13

[27] Boada, M.J.L., Boada, B. L., Munoz, A., Diaz, V. (2006). Integrated Control of Front-Wheel Steering and Front Braking Forces on the Basis of Fuzzy Logic, *Proceedings of the Institution of Mechanical Engineers: Part D – Journal of Automobile Engineering*. 220: 253–267.

[28] Jianhua, G., Liang, C., Feikun, Z., Liang, Y. (2011). Coordinated Control of AFS and ESP Based on Fuzzy Logic Method. International Conference on Mechatronic Science, Electric Engineering and Computer, August 19-22, 2011, Jilin, China.

[29] Goodarzi, A., Alirezaie, M. (2009). Integrated Fuzzy/Optimal Vehicle Dynamic Control. *International Journal of Automotive Technologies*. 10: 567.

[30] Yağiz, N., Sakman, L.E., Guclu, R. (2008). Different Control Applications on a Vehicle Using Fuzzy Logic Control. *Sadhana*, 33(1): 15- 25.

[31] Rao, V.C.D., Prahlad, V. (1997). A Tunable Fuzzy Logic Controller for Vehicle-Active Suspension Systems. *Fuzzy Sets and Systems*, 85: 11-21.

[32] Barr, A. J., Ray, J. I. (1996). Control of an Active Suspension using Fuzzy Logic. Proceedings of IEEE 5th International Fuzzy Systems, New Orleans, LA, 1, pp. 42-48.

[33] Al-Holou, N., Lahdhiri, T., Joo, D.J., Weaver, J., Al-Abbas, F. (2002). Sliding Mode Neural Network Inference Fuzzy Logic Control for Active Suspension Systems. *IEEE Transactions on Fuzzy Systems*, 10(2): 234-246.

[34] Gandhi, P., Adarsh, S., Ramachandran, K.I. (2017). Performance Analysis of Half Car Suspension Model with 4 DOF using PID, LQR, FUZZY and ANFIS Controllers. *Procedia Computer Science*, 115: 2-13.

[35] Lian, J.C. (2013). Enhanced Adaptive Self-Organizing Fuzzy Sliding-Mode Controller for Active Suspension Systems. *IEEE Transactions on Industrial Electronics*, 60(3): 958-968.

[36] Singh, A.S.P., Darus, I.Z.M. (2014). Active Roll Control Strategy Using Fuzzy Logic Control Active Suspension. *WSEAS Transactions on Systems and Control*, 9(1): 566-573.

[37] Kadir, Z. A., Hudha, K., Jamaluddin, H., Ahmad, F., Imaduddin, F. (2011). Active Roll Control Suspension System for Improving Dynamics Performance of Passenger Vehicle. Proceedings of 2011 International Conference on Modelling, Identification and Control, Shanghai, pp. 492-497.

[38] Kawashima, K., Uchida, T., Hori, Y. (2010). Rolling Stability Control of In-wheel Motor Electric Vehicle Based on Disturbance Observer, Motion Control, Federico Casolo (Ed.), In Tech, Available from: https://www.intechopen.com/books/motion-control/rolling-stability-control-of-in-wheel-motor-electric-vehicle-based-on-disturbance-observer [Accessed 31 October 2017].