CHAPTER 2

LITERATURE SURVEY ON FUZZY AND INTEGRATED FUZZY LOGIC CONTROL SYSTEMS

The historical development of fuzzy logic, fundamentals of fuzzy set theory and the basics of control strategies are introduced in the previous chapter for better understanding and design of the fuzzy controllers. This chapter covers the comprehensive general and specific literature survey on fuzzy and integrated fuzzy logic control systems for process parameters such as speed, position, and temperature and motivation for the present work is presented in the end.

2.1 General Literature Survey

The basic idea of fuzzy sets was introduced and outlined in the year 1964 by Lotfi A. Zadeh, a well-respected professor in the department of electrical engineering and computer science at University of California, Berkeley [1-5]. The idea of applying fuzzy sets to the control problems was presented for the first time by Zadeh and Chang [6,7]. E. Mamdani and Assilian initiated the actual research on application of fuzzy logic controllers in United Kingdom around the mid-70s [8,9]. They developed the first fuzzy logic controller, which was for controlling a steam generator. Mamdani’s work influenced and inspired other research workers to explore the applicability of fuzzy controller [10-12]. In 1976, the first industrial application for fuzzy logic controllers was developed and applied to the control of a cement kiln [13]; according to the literature, this was the first commercially available fuzzy controller and the system went to operation in 1982. In the late 1980s, the interest in fuzzy controllers increased very rapidly in Japan. This increased interest was likely as an outcome of the first implementation of fuzzy control in a significant project, an automatic-drive fuzzy control system for subway trains in Sendai City. Another early successful industrial application of fuzzy logic was a water-treatment system developed by Fuji Electric. Fuzzy controllers have also been installed with great success in broad variety of consumer products, including washing machines, refrigerators, video cameras, vacuum cleaners, automobiles, TV sets, and many others. Few examples are fuzzy control system for an unmanned helicopter, model car and helicopter flight control [14-16], a project headed by Sugeno at the Tokyo Institute of Technology, which has been completed and tested. Another example is a fuzzy controller that can stabilize a triple inverted pendulum [17]. Research on
fuzzy controllers in the 1990s is also characterized by exploring the integration of rule-based and model-based approaches in fuzzy control, as exemplified by the work of Filev [18,19] and Sugeno and Yasukawa [20]. By investigating connections between fuzzy controllers and neural networks, Kosko presented a new approach for adaptive fuzzy systems using neural networks [21]. By 1990, fuzzy logic reached the consumer market [22,23]. By the mid-1980s, the fuzzy chip and fuzzy hardware started gaining importance. Yamakawa’s fuzzy hardware of analog mode is described in several papers [24-29]. Other approaches to fuzzy logic hardware are described in Gupta and Yamakawa [30], and Diamond et al. [31]. An important contribution to fuzzy logic hardware is a design and implementation of a fuzzy flip-flop by Hirota and Ozawa [32]. This is a memory that allows us to store one-digit fuzzy information. It is essential for implementing multistage procedures of fuzzy inference.

In the development of fuzzy set theory, three natural phases can be identified [33]: In period 1965-77, often referred to as the academic phase, is characterized by the development of fundamentals of fuzzy set theory and only initial speculations about prospective applications of the theory. The outcome was rather a small number of publications of a predominantly theoretical nature by a small number of contributors primarily from the academic community.

The period from 1978-88, referred to as the transformation phase, is characterized not only by significant advances in fuzzy set theory, but also by some successful practical applications of the theory. The number of contributors, some of them from industry and business, increased rapidly. This resulted in a substantial increase in relevant publications, some of which discussed various engineering applications. It is also significant that some important professional societies and journals devoted to fuzzy set theory and its applications were established during this period.

The current period which began in 1989 and is often referred to as the fuzzy boom, is characterized by a rapid increase in the successful industrial and commercial applications of fuzzy set theory, which has resulted in very impressive revenues. Some major companies, initially in Japan, endorsed fuzzy set theory and committed resources to its further development. Major research centers, devoted to applications of the theory were established. This has all been accompanied by a tremendous increase in the number of relevant publications including several dedicated journals. At the same time, computer software and hardware designed for various applications of fuzzy set theory have become commercially
available in increasing variety. In the early 1990s, fuzzy set theory became recognized as one of the key ingredients of the emerging area of soft computing. The aim of soft computing is to exploit, whenever possible, the tolerance for imprecision and uncertainty in order to achieve computational tractability, robustness, and low cost by methods that produce acceptable approximate solutions to complex problems which are often not precisely formulated. In soft computing, the main partners of fuzzy set theory are neural networks and genetic algorithms.

The growth of fuzzy set theory and particularly its applications are well and thoroughly depicted in several books [34-46]. The literature survey in fuzzy logic controllers is a Herculean task. For example, Klir and Yuan cited 1731 references in the bibliography [36]. Similarly John Yen and Reza Langari cited 721 references on historical growth of fuzzy logic and fuzzy set theory [47]. Pedrycz cited over 300 references on fuzzy sets, analysis and design [48]. Drainkov et al. cited 248 references on fuzzy set theory and FLCs [49]. Sanchez et al. cited 195 references on genetic algorithms and fuzzy logic systems [38]. CD-ROM database of INSPEC has hundreds of references every year and the IEEE explorer also provides extensive literature on fuzzy logic in its current and previous journals. Therefore, only salient literature survey is presented in view of the specific applications considered in this thesis.

2.2 Fuzzification and Defuzzification Methods

Li Zheng proposed a practical method for tuning a PI like fuzzy controller. He proposed easier and faster tuning techniques and he employed triangular memberships function for fuzzification. He also reported a practical computer-aided tuning technique for fuzzy control. Triangular membership functions and center of gravity technique employed for fuzzification and defuzzification respectively [50,51]. T. H. Lee et al. reported position control for wheeled mobile robots using fuzzy logic controller, the FLC employed triangular membership function for fuzzification and center of gravity technique for defuzzification [52]. Mohamadien and Stonier developed a method to tune and optimize the membership functions of the FLC by using genetic algorithms [53]. Tetsuji Tani et al. illustrated a practical method of control using PID and fuzzy control for the top temperature of a petrochemical plant. They used triangular membership function for fuzzification [54]. Zazo et al. reported direct fuzzy control applied to a level process. They used triangular
membership functions and COG defuzzification method, to get accurate output for any set point for a SISO nonlinear level process by fuzzy logic technique [55]. C. K. Lee et al. reported the fuzzy tuned PD controller for DC motor drive. They employed triangular membership functions for fuzzification and centre of gravity for defuzzification [56]. Xie Kanglin and Fu Jinyou reported determination of membership functions and fuzzy rules of a neural network fuzzy logic controller system. The problem of how to find the most optimal fuzzy rules and input/output membership functions in developing a fuzzy control system and a study of neural network has been presented [57]. Castro reported on how many rules were necessary to get a 'good' fuzzy controller for a control problem. He has given an upper bound answer to this question with product conjunction, triangular membership functions and weighted sum of centroid defuzzification [58]. Eminoglu and Altas reported the effects of the number of rules on the output of a fuzzy logic controller employed for a PMDC motor. The sensitivity of the FLC with respect to variations in the rule decision table is tested by changing the original decision table in the range of ±30 % [59]. Tamaki et al. reported identification of membership functions based on fuzzy observation data. They proposed a method to obtain the membership functions that satisfy the restriction of the fuzzy event against the given possibility density function [60]. Soumitra Kumar Mandal et al. described the fuzzy logic controller based position control using induction motor. They used triangular membership functions for fuzzification and Max-Min method for defuzzification [61]. H. L. Tan et al. reported a dynamic input membership scheme for a fuzzy logic DC motor controller. They employed triangular membership functions for fuzzification and center of gravity technique for defuzzification. The dynamic membership scheme employed center width narrow, center width constant and center width wide membership functions [62]. Zhi Liu et al. reported a probabilistic fuzzy logic system for modeling and control where they employed bell-shaped membership function for fuzzification and center of gravity for defuzzification [63].

Defuzzification of fuzzy intervals was addressed by Zhao and Govind [64]. A defuzzification based upon the principle of uncertainty invariance was proposed by Klir [65]. General classes of parameterized defuzzification methods were explored by Filev and Yager [66,67]. Yager and Filev also reported SLIDE: A simple adaptive defuzzification method and on the issue of defuzzification and selection based on fuzzy sets. They also showed how a proper defuzzification method could be determined by learning algorithms [68,69]. An interesting strategy for dealing with the defuzzification problem, based on sensitivity
analysis, was developed by Mabuchi [70]. An overview of defuzzification methods was prepared by Hellendoom and Thomas [71]. Rao and Saraf reported theoretical study of defuzzification methods of FLCs for speed control of DC motor [72].

2.3 Application of Fuzzy and Integrated Fuzzy Logic Controllers for the DC Motor Speed Control System

DC motors are finding wider applications in the industry such as robotics, guided vehicles, chemical processes etc. Motor control for accurate positioning and speed is a very important function in many applications. Significant research has been done on the motor speed and position control using various controllers.

Sharaf et al. reported a fuzzy logic speed controller for DC motor drives. The final control was adjusting the firing delay angle of a six-pulse converter rectifier [73]. Govind and Hassan described the application of fuzzy logic to control the speed of a 5 hp industrial size DC motor. The algorithm to compute the manipulated variable was written in ‘C’ language to achieve real time speed control. They also discussed the fuzzy logic speed control in the field of power electronics [74]. Lim reported experimental study of a fuzzy system for DC motor control. He proposed a new method of designing a fuzzy logic controller for DC motors. In this method, the input signal to a class of conventional fuzzy logic controller is modified so that the performances of the overall system can be enhanced [75]. Tseng and Teo reported computer control of DC-motor with fuzzy logic. A case study of fuzzy logic in controlling a DC-motor without the knowledge of the model was presented. They examined the problem of regulating the speed of a servomotor in the presence of intermittent frictions. The experimental results clearly demonstrated the satisfactory control action by their fuzzy logic based computer control [76]. De Azevedo et al. reported a fuzzy controller for position control using DC machines. They used DC motors coupled to a gearbox. Most of the results were presented in comparative terms between the PID classical controller and the FLC. In their application, the FLC proved to be better than the PID because PID is highly sensitive to the load (torque) disturbances while the FLC is almost insensitive [77].

Ming-Yuan Shieh and Li proposed an outline for design of Integrated Fuzzy Logic Controller (IFLC). They applied the proposed structure to improve the original control system. A DC servo motor (Feedback MS 150) simulation is exploited to address the
existence and the superiority of the IFLC system. They designed and implemented an IFLC for DC motor servo system. This controller improved the performance as the motor load changes. This controller was particularly effective in position control of a DC-servo motor under shaft frictional load, inertia disk load and mixed frictional/inertial load conditions [78,91,109]. Kosc et al. reported robust fuzzy logic control for DC motor speed-loop. They applied classical Proportional-Integral, FLC and their combination. Results showed the best performance of a Proportional-Integral FLC in the sense of robustness to the inertia variations and to the load torque disturbances [79]. Le-Huy and Hamdi reported control of a direct-drive DC motor by fuzzy logic. They presented the design of a FLC for position control of a single-link robot arm. FLC was implemented on an 8-bit microcontroller (68HC11) to evaluate the obtainable performance with a low-cost processor. Good experimental results were obtained illustrating the high robustness of the controller to the load mass change [80].

Guillemin reported universal motor control with fuzzy logic. He described the design of Fuzzy Logic motor control with a standard low-end microcontroller and fuzzy logic development tool [81]. Lee and Pang dealt with the adaptive control of a DC motor using fuzzy algorithms. FLC attempts to compensate for the parameter variations in the system. They also illustrated how to construct the fuzzy rules and membership functions, which leads to implementation of FLC and obtained the simulation results [82]. Sikunab H. F. et al. reported a novel fuzzy logic control scheme to regulate the speed of a permanent magnet DC motor drive via armature voltage control. The proposed fuzzy logic rule based controller scheme utilizes both motor current and speed errors. The firing delay angle of the 3-phase converter is determined as the output of a modified weighted center of area (wcoa) defuzzification stage, with an assigned rule base [83]. Zuhlke reported fuzzy logic for control of linear displacement servomotor drive. He presented a comparison of PID and fuzzy control. The use of ASIC for implementation of FLC system is noted and it is reported that the performance of fuzzy controlled servomotors was better than PID under practical nonlinear conditions [84]. El-Khouly et al. reported fuzzy logic based controller and ANN based controller for speed control of PMDC motors. The experimental results validate the good dynamic speed tracking performance of the speed controllers [85].

Malki and Feigenspan used a fuzzy proportional-derivative controller to control the speed of a permanent magnet DC motor with a load. The performance of the fuzzy PD
controller was tested with an experimental setup of a motor-generator with a load and was then compared to the conventional digital PD controller. This comparison revealed that the fuzzy PD controller reduced steady state error, thus maintaining the speed at the set point [86]. Hamaifar et al. reported fuzzy controller for robot arm trajectory. They proposed a hybrid implementation of fuzzy logic controllers and conventional PID controllers and applied it to a 2 degree of freedom robot arm with promising results [87]. Lee and Pang described the fuzzy logic approach to design a robust brushless DC motor controller for variable speeds. Such a robust controller consisted of a PI controller tuned by fuzzy logic. It demonstrated that brushless DC motor speed control system was tuned to provide an optimal response for variations in system parameters [88]. They also described an auto-tuning method for a brushless DC motor control system using a digital signal processor with fuzzy logic algorithms. Computer simulation showed that the brushless DC motor system could be automatically tuned to provide an optimal response for variations in system parameters [89]. Yousef and Khalil applied fuzzy logic to a DC motor drive system. Two fuzzy controllers were proposed for the drive system, namely, speed and current controllers. Fuzzy control laws were developed to regulate the motor speed and maintain the current at a limiting value. The simulation results clarified superiority over classical PI controllers. [90].

Cheng-Liang Chen and Feng-Yuan Chang described the design of a neural/fuzzy proportional-integral-derivative controller. The neural/fuzzy PID controller has the same basic structure of conventional PID, but its parameters could be changed according to local conditions. A neural network or a fuzzy system was used for constructing nonlinear relationship between controller parameters and local control conditions. Results demonstrated applicability of such a controller for controlling a highly nonlinear neutralization process [92]. Gong Huajun designed intelligent high precision fuzzy PID controller for a digital servo system and achieved good results for better dynamic and static performances and robustness [93]. Yao-Yu Hsu et al. proposed a new learning method to automatically generate a speed controller for a brushless DC motor without requiring its mathematical model. Control strategies are extracted from the experimental data and recorded into a table which is considered as a fuzzy rule base after learning and is used to control the plant in a closed loop form [94]. Guilleman P. implemented fuzzy logic in a standard microcontroller to regulate the speed of a universal motor by a real time adjustment of the motor current. The microcontroller directly tunes the motor current by means of a chopper converter. This paper also gives the practical procedures to define the input...
parameters and procedure to build fuzzy logic rules while using the fuzzy logic development tool [95]. Eminoglu et al. applied fuzzy logic for speed control of a PMDC motor. The proposed method for the fuzzy rules was based on the comparison of possible transient responses of the system output and the reference set point. Desired performance of the overall scheme was obtained by simulation [96].

Denai et al. applied fuzzy logic to the control of a separately excited DC motor. A fuzzy PID controller has also been evaluated and compared with standard FLC [97]. Sugisaka et al. presented results of running tests of a mobile vehicle. A fuzzy-PID controller was used in the control systems of the mobile vehicle. The proportional gain $K_p$, derivative gain $K_d$ and integral gain $K_i$ of PID controller were adjusted continuously by fuzzy control method during running of the mobile vehicle [98]. Wee Zhi Qiao and Mizumoto proposed a PID fuzzy controller structure, which retains the characteristics similar to the conventional PID controller, and they tuned the parameters of PID type fuzzy controller on line, producing a parameter adaptive fuzzy controller [99]. Inoue et al. described an advanced control method of system parameter auto-tuning implementation for a DC brushless motor drive system using fuzzy reasoning logic with an automatic learning control function. They practically confirmed the feasible effectiveness of auto-tuning processing approach for DC brushless servomotor drives through experimental results [100]. Chao-Shu Liu et al. proposed a robust controller scheme applied to brushless servo drives. They utilized DSP TMS320C25 to convert phase current into sinusoids. They performed the experimental studies on DC brushless servo drive for load variation and internal disturbances [101].

Akbarzadeh et al. reported that in classical application of fuzzy logic, there is a great dependency on proper expert knowledge acquisition. But they removed the dependency by using a genetic algorithm to automatically determine parameters of fuzzy rule sets such as membership functions. This method was useful for search in GA-hard landscapes and was successfully applied to speed regulations of a DC motor [102]. Denai and Hazzab presented the simulation and real time results for the separately excited DC motor using fuzzy PID controller [103]. Malki et al. presented the design and experiment of a fuzzy PID controller for a flexible joint robot arm with uncertainties from time-varying loads. The proposed design was tested using a flexible joint robot arm driven by a DC motor in a laboratory, where the arm experienced time-varying loads. Control performances by the conventional and fuzzy PID controllers were compared [104]. J. L. Silva N. and Hoang Le-Huy described
an improved fuzzy learning algorithm for motion control applications. The objective of the fuzzy logic adaptation mechanism was to change the rules definition in the FLC rule base table, according to the comparison between a reference model output signal and the system output. They implemented the algorithm on TMS320C30 DSP. They also presented simulation results [105]. Abdollah Khoei et al. proposed design of a novel fuzzy logic controller for DC motor speed control system. The experimental results showed that the proposed FLC system has a smaller overshoot and rise time [106].

Mishra et al. reported development of a FLC for servo systems used for position control. The simulated results show the superiority of FLC over classical controllers for change in system parameters and load disturbances [107]. Betin et al. applied fuzzy logic principle to control the speed of a stepping motor drive with feedback. An advanced test bed was used in order to evaluate the tracking properties and the robustness capacities of the fuzzy logic controller when variations of the mechanical configuration occur. The experimental set up used 16-bit microcontroller [108]. Kreindler et al. presented a new control scheme for a brushless DC servomotor using fuzzy logic for the speed control. A complete series of tests were accomplished, both at no-load and at load variations. The results obtained with the proposed fuzzy control structure were compared with those from a classical PI speed controller structure. An increased robustness of the system at load variations was observed, as compared with classical PI speed controllers [110]. S. Tunyasrirut et al. reported an adaptive fuzzy PI controller for speed of separately excited DC motor. The experimental results showed that the step responses of the speed of the DC motor controlled by the adaptive fuzzy PI controller had small overshoot as compared to PI cascade controller [111]. Amar El Z. and Walid Ahmed M. illustrated the application of fuzzy logic in a speed control system that uses a single phase, fully controlled B2C converter bridge driving a separately excited DC motor. The experimental results indicated the benefits of fuzzy logic in the field of DC drives [112].

Cakir et al. proposed a new control method of a separately excited DC traction motor using fuzzy logic. The drive system has been simulated and results have been compared with those obtained by a conventional PID controller. The proposed controller exhibits superior transient and steady state performance compared to the usual PID controller [113]. Betin et al. also applied PID control, self-tuning regulator and FLC for speed control of stepper motor drive in a closed loop. These three controllers were compared by simulation and FLC
was found to be the best regulator for their application [114]. Lim et al. described an experimental study to investigate the effectiveness of applying a supervisor to enhance the performance of fuzzy logic controller for position control of a DC motor in the presence of a large variation in the inertia load coupled to the motor. Experimental results showed that the said supervisor significantly enhanced the performance of the fuzzy logic controller over a wide range of inertia loads and for different system gains [115]. Y. Tipsuwan and M. Y. Chow described a method to implement a fuzzy logic speed controller for a DC motor using a Fuzzy logic microcontroller. They discussed hardware design and implemented fuzzy control algorithm on a 16-bit microcontroller Motorola 68HC812A4. The experimental results were presented for load and no-load conditions [116]. Bhim Singh et al. proposed a microcontroller based speed controller for permanent magnet brushless DC motor. An assembly language program is written to realize Pi speed controller. The experimental results obtained from a prototype drive were shown and conformed the validity of the simulated results [117].

Rubaai et al. described the design and experimental verification of a hybrid fuzzy control system for a high performance brushless DC motor drive. Performance of the hybrid fuzzy-PI controller is evaluated through a laboratory implementation. Experimental results have shown excellent tracking performance of the proposed control system, and have convincingly demonstrated the usefulness of the hybrid fuzzy controller in high performance drives with uncertainties [118]. Ismail A., and Sharaf A. M. illustrated a novel energy efficient neuro fuzzy speed regulation scheme for permanent magnet DC motor and separately excited industrial type motor drives. They presented simulation results using MATLAB/SIMULINK software package [119]. A. Khoei et al. designed PC-based fuzzy controller for controlling the speed of a dc motor. The proposed controller results in a reduced chattering around the set point. The experimental results presented the step response of the system [120]. M. S. Mostafa et al. reported the application of fuzzy neural networks (FNN's) in identification of DC motor drive system. The FNN technique compensates the drawbacks of fuzzy logic controller with fixed membership function and quantization levels. Comparison between FLC and proposed FNN was demonstrated. They experimentally showed that the performance of FNN was superior to the FLC [121].
2.4 Application of Fuzzy and Integrated Fuzzy Logic Controllers for DC Motor Position Control System

Pierre Sicard et al. investigated DC motor position control using sliding mode and disturbance estimator. They presented simulated results and responses of the system with minimum inertia and load torque to a step response of 1 rad [122]. Chung-Yuen Wan et al. described a vector-controlled induction motor position servo motor drive where fuzzy control was used to achieve robustness against parameter variations and load torque disturbance effects [123]. Jong Sun Ko et al. presented a new control for the robust position control of a brushless direct drive (BLDD) motor using FLC. The integral-proportional position controller plus fuzzy logic speed controller was employed to obtain the robust BLDD motor system. The experimental results showed the performance of each control algorithm for the BLDD machine [124]. Suyitno et al. proposed a variable structured robust controller whose structure is continuously changed by fuzzy logic so that the system responds quickly if the error and its rate is large and vice versa. They showed that such a controller is insensitive to both the plant noise and the observation noise [125]. Haraldo Rodrigues De Azevedo et al. proposed a fuzzy logic controller for DC motor position control. The results were presented in comparative terms among fuzzy logic controller, sliding mode controller and PID controller. In this application FLC proved to be better than the PID because PID is highly sensitive to the load changes while FLC almost insensitive [126].

Paul-Hai Lin et al. reported comparison on fuzzy logic and PID controls for a DC motor position controller. For comparison purpose, both fuzzy and PID control algorithms were implemented in a 486-based PC with C program development tools. The experimental results showed that, PID control settling time given as minimum 198 ms for a step size of 90° and for the same the FLC has the 180ms. The conclusion drawn form the results were the FLC has got better performance over PID [127]. Jong-Hwan Kim et al. reported fuzzy precompensated PID Controllers. They demonstrated the performance of their scheme via experiments performed on a DC servomotor position control tested under varying load conditions. They showed that the results of fuzzy precompensated PID controllers are superior to the conventional PID controller [128]. Senyu et al. proposed robust position control of DC servomotor using fuzzy reasoning to consider the estimation error. In order to compensate the estimation error, they combined the equivalent disturbances torque observer
and a feedback controller. They introduced fuzzy control for the highly nonlinear estimation error [129]. Bay et al. used fuzzy logic to control a brushless DC servo motor drive. The proposed controller of the position and speed are designed and simulated. The results of applying the FLC for BLDC motor are compared to those obtained by the application of conventional PI system. The results showed the superior performance of FLC, and its insensitivity to the changes in operating conditions [130]. Pai-Yi Huang et al. designed fuzzy sliding mode controller (FSMC) based on real-coded genetic algorithm (RGA) for precision positioning. The real-coded genetic algorithm uses the internal floating-point representation of the computer system. The RGA based FSMC was applied to a high precision system. XY-table with high a high-resolution laser scale (0.1μm) was used as demonstration plant. The experimental results showed the position error and the control voltage [131].

Jung Sun Ko et al. also presented a simple control for the robust position control of a brushless direct drive (BLDD) motor using FLC. The integral-proportional (IP) position controller plus fuzzy logic speed controller was employed to obtain the robust BLDD motor system, which was approximately linearized using the field orientation method for an AC servo. Using the microprocessor, FLC controls the overall system and the robustness was also obtained without affecting the overall system response [132]. Jong-Bae Lee et al. reported a low-cost speed control system using a FLC for a brushless DC motor. They used Hall IC signal for the permanent magnet rotor position and for the speed feedback signals, and also for an 8-bit microcontroller (80CL580). Simulation for FLC algorithm was done with MATLAB program. They verified the performance for unit step response [133]. R. Okuno et al. developed microprocessor based DC motor position control system for myoelectric hand. They employed PWM technique to control power to the system and the experimental results were presented for control of angle and control compliance [134]. Cheok and Ertugrul described the robustness of a fuzzy logic based angle estimation algorithm for the switched reluctance motor. It was shown that the fuzzy logic based scheme was robust to erroneous and noisy signals commonly found in motor drives [135]. Dumitriu presented the concept and implementation of an intelligent motion controller for a brushless DC motor. A digital signal processor-based hardware setup TMS320F240 and a specialized software environment are used in laboratory experiments. Actual experimental results obtained showed the effectiveness of the proposed intelligent motion controller [136].
Jianxin Tang reported real time DC motor speed and position control using the low-cost TMS320C31 digital signal processor kit. He designed PID controller and implemented in assembly language program. His results showed that, with the PID controller the desired position was obtained with out overshoot [137]. Kelvin R. Aaron et al. developed a closed loop DC motor control system using National Instrument’s (NI) Data acquisition (DAQ) Board (Model MIO 6040) and LabVIEW software package and DAQ Signal Accessory Board for smooth and accurate positioning. The results showed that the motor position and its velocity for a total rotation of 60 degrees and a final time of 10 seconds [138]. S. Liu et al. presented a robust tracking controller design for a short-stroke permanent magnet motor as a linear drive. They designed PI and PID controllers. The simulation results were performed using real actuator data. Even in the presence of high value exponential disturbance force, tracking of smooth trajectories carried out with errors not more than ± 60 microns [139]. Ying-Shieh Kung et al. designed high performance position controllers based on TMS320F2812 DSP. In their experiment, an adaptive fuzzy logic controller with triangular membership fuzzifier, product-inference rule and center of average defuzzifier was applied in position control loop to test the dynamic performance of the motor. The experimental results demonstrate the step and frequency command responses of the system [140]. T. H. Lee et al. described the design and development of a fuzzy logic controller for the position control of wheeled mobile robots (WRMs). They employed triangular membership function for fuzzification and center of gravity method for defuzzification. The simulation results of fuzzy and fine tuned PID control responses are presented in a comparative fashion [52]. Ming-Yuan Shieh et al. demonstrated implementation of integrated fuzzy logic controller for servomotor system. The MS150 modular servo system was employed in this application. The experimental results indicate that the IFLC system provide better system responses than those of the PID control system [109].

2.5 Application of Fuzzy and Integrated Fuzzy Logic Controllers for Temperature Control System

Temperature is an important process parameter, which is measured and controlled in most of the industries. Precise control of the temperature is desirable in many processes. Earlier control systems employed conventional controllers. Further, the performance and stability of the system are improved by employing expert controllers (FLC and IFLC).
Hara and Kanai reported adaptive fuzzy control for room air conditioners with improved efficiency and reduction in fluctuations as compared to PID controllers [141]. Shimozawa et al. reported rice-cooking control by fuzzy logic that allows more delicate adjustment and fine results in cooking [142]. Sakai and Uchida proposed fuzzy logic for microwave oven. It obtained the best cooking results regardless of the quantity of food, shape of container, wrap, cover or initial temperature [143]. Kuraseko T. et al. reported full-automatic washing machine using fuzzy logic controller. This new system with fuzzy logic delicately controls the factors affecting three sensors (water temperature, washing load, and fiber type) and selected the best washing cycle [144]. Infelise N. proposed a clear vision of fuzzy logic by taking temperature control an example. He compared fuzzy control with PID control and considered fuzzy control based programmable logic controller (PLC) [145].

Tobi T. and Hanafusa T. illustrated a practical application of fuzzy control for an air-conditioning system and presented the results of simulation and practical use [146]. Grossi P., and Scattolini R. reported PID, predictive and fuzzy temperature control for nuclear magnetic resonance spectroscopy experiments. They showed superior performance with respect to PID control of a simulated plant model and of the real plant [147]. Tani T., and Tanaka K. proposed a design method of fuzzy-PID combination control system and its application to heater outlet temperature control. They also reported that the fuzzy-PID combination control system could control heater outlet temperature perfectly not only in the stationary state condition but also in non-stationary conditions such as start-up, shutdown, and feed switching [148]. Zhang Huaguang et al. reported a kind of fuzzy self-tuning regulator and its application to temperature process control in boiler-turbine unit with a simulation study. They showed that fuzzy approach was superior to the conventional series PID approach [149]. G. A. Pereira et al. proposed fuzzy algorithm for refinery feed-heater temperature control. The fuzzy logic controller used 7 member triangular fuzzifier and center of gravity defuzzifier. With their results, they recommended the use of fuzzy controllers in oil refineries for precise feed outlet temperature control [150].

An European company introduced FLC to a new generation of furnace controllers in a private home heating system. The FLC and conventional control algorithms were implemented on 8-bit microcontroller. The FLC control system possessed better performance over the conventional PID control system [151]. Vom Berg proposed the fuzzy logic: a clear choice for temperature control for processes with two or more variables. He
compared FLC with conventional PID controller [152]. Isaka described fuzzy temperature controller and its applications to an industrial temperature control system [153]. Sugawara and Suzuki reported application of fuzzy control to air conditioning environment taking home and rail car air conditioners as examples [154]. Wang and Rad compared the performance of a fuzzy controller using input mapping and output mapping factors with that of a traditional PID control algorithm. They demonstrated both by simulation and experiment on the plant. FLC provided better control and had better disturbance rejection properties [155].

Ramaswamy et al. described a fuzzy logic controller design for nuclear power plant for a wide range of temperatures. The fuzzy logic controller showed good performance and stability [156]. Daca W. et al. reported fuzzy logic for temperature control. A fuzzy controller based on freely programmable process computer allows real temperature control [157]. Rubiyah Yusof et al. presented self-tuning PI and PID controllers for water bath temperature control system. They studied the system performance for set-point variation and under the influence of load disturbances [158]. P. Isomursu et al. designed and developed a self-tuning fuzzy logic controller for temperature control of superheated steam. They described two self-tuning adaptive methods. The self-tuning mechanisms made the FLC more robust and portable. The test results showed Adaptive FLC handles disturbances better than cascade PI generally used for controlling the temperature of superheated steam [159].

David A. Gwaltney et al. developed fuzzy control algorithm of wind tunnel temperature processes in the M6HRNT at NASA Langley Research Centre. Automatic control of pressure, flow and temperature processes was achieved using Intel 486/125 microprocessor board. The FLC algorithm is implemented using 'C' language [160].

Yusof R. et al. reported the application of self-tuning PI (PID) controller to a water bath (Yamato Science Inc. BT-15 model) temperature control system. The complete setup was interfaced to the computer and control algorithms were developed using 'C'. The results showed that the self-tuning PI performed better than PI controller [161]. Jack Wilkinson described the additional advances in fuzzy logic temperature control. He given overview on fuzzy logic, fuzzy control methods, new advances in fuzzy logic and their application to temperature control [162]. Taur et al. reported temperature controller of a plastic extrusion barrel using PID fuzzy controller and demonstrated that the PID fuzzy control algorithm can meet requirement of their temperature control project [163]. Ladera et al. reported a fuzzy
logic controller with switching knowledge base for industrial process control. The results demonstrated the utility and efficiency of fuzzy control to control an industrial process with long range and fast changing characteristic variables and great adaptability [164]. Frank and Hebrick reported model-based design of a fuzzy temperature control for a steam generator. They compared FLC with PI controller [165].

Feddem and Gebhardt proposed fuzzy logic for air conditioning control using MATLAB [166]. Ge Bo described the temperature control for microwave oven based on single chip computer. The system used low power high-speed temperature control for dual magnetic tubes in the microwave oven [167]. Wang Yaonen reported an intelligent controller using fuzzy neural networks and its application. They presented a new self-organizing controller using fuzzy neural networks and a fast Kalman learning algorithm. Simulation results on temperature control showed that the new intelligent controller had the more significant performance and robustness than conventional fuzzy approaches [168]. Manish and Peng-Yung Woo reported efficiency of fuzzy and adaptive fuzzy controllers relative to PID controllers in temperature control. They illustrated a comparative study among PID, fuzzy and supervisory fuzzy controllers [169]. Ismail A. and Abu-Khousa E. reported fuzzy top brine temperature (TBT) control of multi-stage flash desalination plants. The fuzzy controller obtained good results compared to those obtained from the existing conventional controllers [170].

Putter E. and Gauws J. reported an automatic controller for a green housing using a supervisory expert system. Two control techniques, PID and fuzzy control were investigated and the supervisory expert system with FLC was found to be more user friendly [171]. Occhipinti L. and Nunnari G. reported synthesis of a green house climate controller using AI-based techniques. The paper proposed a framework for the development of a multi-input and multi-output (MIMO) fuzzy logic controller in modern green houses involving non-linear physical model [172]. Knobloch J. and Presberger T. reported optimization of an on-chip fuzzy temperature controller. it consists of a micro system which control the temperature on a sensor-chip and classifies gasses, both by means of fuzzy logic. The results of the optimization, including genetic algorithms and evolutionary strategies, are provided [173]. Prehn E. explained the regulation concepts and fuzzy control by examples. Application of fuzzy control to cascade control of temperature and flow in a heat exchanger, combustion gas/air mixture control and chemical reactor temperature control with fuzzy
parameter adaptation have been discussed [174]. Malki H. A. and Guanrong Chen reported a fuzzy PI controller for boiler systems in power plants with several advantages [175].

Kaur D. and Schroeder R. reported the design and modeling of microcontroller fuzzy nuclear power plant controller. It is a working model of control rod in a nuclear power plant based on fuzzy logic and implemented with an MC68HC11 microcontroller. They developed a fuzzy model, tested its functionality [176]. Bob Coeyman et al. presented a case study of application of intelligent fuzzy logic controller to a production distillation column reboiler temperature control. A performance comparison between the PID and intelligent FLC was illustrated. The results found the FLC reduced temperature overshoot to a minimum and improved valve performance acceptable to operations and maintenance [177]. Fotouhi M., and Garner R used a PID controller in controlling temperature of a multizone furnace. A personal computer was interfaced with the temperature controller for the real time graphical display of the process variables and recording data for further use [178]. Liu Fei and Li Anngna, reported the PLC-based humanized fuzzy control system for steel plate annealing furnace. They implemented temperature control for the annealing furnace of the steel plate [179]. Tani et al. reported fuzzy-PID controller with fuzzy reasoned adaptable control target and its application to petroleum plant in transient state. They obtained good control performance in transient states of feed oil switching and operation mode changing [180]. Lee Jung Mvuna and Yun Jana Bo reported fuzzy-PWM control for adjustment of power rate of a multiple point temperature controller. They designed a temperature controller for a draw and twist machine and applied fuzzy-PWM algorithm to the controller and obtained satisfactory performance [181].

Wang Gaunglana proposed single-chip microcomputer temperature fuzzy control system. He illustrated design method of the single-chip microcomputer thermostat fuzzy control system [182]. Kojak S. et al. reported fuzzy model-based predictive temperature control. The FLC structure has been fine-tuned by implementing the adaptive Neuro-Fuzzy Inference system involved in the fuzzy toolbox of MATLAB simulink ver 5.1 [183]. Seon-Woo Lee et al. worked on a fuzzy logic based pre-compensation method for PI controller to improve the temperature control performance for a variable capacity heat pump (ASH-997). The experimental results showed the effectiveness of the presented control scheme. From the results, steady-state error in degrees was observed as −1.29 and −0.67 for conventional FLC and proposed control scheme respectively [184]. Taur and Chin-Wang Tao described fuzzy
model based approach to the design of PID controllers for temperature control systems. They proposed a fuzzy system identification approach to select the parameters of the PID controller for a plastic injection-molding machine [185]. Keming Xie et al. reported a fuzzy neural network based on the Takagi-Sugeno (TS) model with dynamic consequent parameters and its application to steam temperature control system using MATLAB. The simulated results showed the method is effective, fast in response, minimal in overshoot and robust [186].

Dr. Christine Haissig described an innovative adaptive fuzzy control (AFC) algorithm for regulating the room temperature in a hydronic heating system. The performance of AFC validated using both the simulation and laboratory testing. Their results showed that AFC had better control quality than PI and the AFC spent more time within ± 0.25°C of the set point [187]. Un-Chul Moon and Lee reported temperature control of glass melting furnace with fuzzy logic and conventional PI control [188]. Zhiqiang Gao et al. developed a closed loop control system using fuzzy logic for a class of industrial temperature control problems. The potential of FLC in both software simulation and hardware test in an industrial setting was demonstrated. The results showed the comparison of PID and FLC outputs and significant improvement in maintaining performance and stability over a wide range of operating conditions [189]. Chia-Feng Juang et al. investigated PC based temperature control by using a TSK-type Recurrent Neural Fuzzy Network (TRNFN) controller. They performed experiment on a real water bath temperature control system. In order to measure temperature (using PT100) and send control signals to the heater they used PCI-1710 card developed by Advantech. Co., Ltd. It also provides multiple 12-bit A/D and D/A channels. The results of the system showed TRNFN had the superior performance over the generally adopted BPNN controller [190]. Yi’nan Guo et al. proposed application of fuzzy logic controller for coke oven temperature control. They introduced coke oven heating temperature fuzzy control strategy according to the analysis of factors, which influence flue temperature. The experimental results showed the responses of both the manual and fuzzy control [191].
2.6 Application of Fuzzy and Integrated Fuzzy Logic Controllers for AC motor Speed Control System

The most common family of motors used in the home, business, and industry applications is the AC induction motor. The AC motor operates longer than DC motor with less periodic maintenance. The AC motor provides several advantages over DC motor; hence AC motors are widely used in industry applications. Many researchers have proposed different controllers for AC motor speed and position control applications.

Egan M. G. et al. reported an application specific integrated circuit (ASIC) was presented which acts in conjunction with a standard microcontroller (8031) to produce a compact and effective AC motor control system. The system was based upon synchronous PWM waveform generator for AC motor control applications [192]. Fernades B.G., and Pillai. S. K. described speed control of transistorized PWM inverter fed induction motor with selective harmonic elimination and current controlled scheme using PC [193]. Cleland J., et al. illustrated fuzzy logic control of AC induction motors. They investigated fuzzy logic control of electric motors to reduce energy consumption when motors were operated at less than rated speeds and loads. Simulated results of microprocessor based fuzzy logic motor controller were described [194]. Ashrafzadeh F. et al. reported a design approach of a self-organizing and self-tuning fuzzy logic controller for field-oriented control of induction motor. The suitability of the genetic algorithm optimization technique as a means to determine and optimize the fuzzy logic controller was discussed. The experimental results compared performance of conventional FLC with the auto-design FLC [195]. Fodor D., et al. proposed fuzzy logic-based energy optimizer for AC motors. A FLC field oriented drive was designed, simulated and experimented in a speed control loop. The results are compared with those obtained on the same drive with conventional PI type speed controller. They concluded that FLC obtains better responses [196].

John C. C. et al. reported a fuzzy logic, energy optimizing controller design to improve the efficiency of motor/drive combinations running at various load and speed conditions. The proposed controller was experimented on a 10 hp NEMA B motor. Experimental results of optimal efficiencies achieved using the fuzzy logic energy optimizer vs. efficiencies achieved by the ASD operated as normal [197]. Von Altrock C. and Beierke S. discussed fuzzy logic enhanced control of an AC induction motor with a DSP TMS320C31. They discussed field oriented control method and fuzzy flux control method.
The experimental results showed fuzzy logic approach got the better performance and higher robustness than the traditional approach. MATLAB/Simulink and fuzzy TECH did the system simulation [198]. Ying-Yu T., and Tien-sung K. reported design and implementation of an FPGA-based motor control IC for permanent magnet AC servomotors. All the control functions, including the PWM waveform generation, current control, vector control, velocity control, and position control have been realized using FPGA based programmable logic gates. The experimental results were verified with a single chip DSP TMS320C14 [199]. Ying-Yu T., and Jin-Yi Jyang, designed a programmable current vector control IC for AC motor drives. A digital current vector scheme realized using CPLD. The experiment was carried out on a HP PM ac servo motor and experimental verification was carried out using 8051 microcontroller [200]. Cataliotti A. et al. presented two soft computing techniques and applications to a fuzzy logic control system for an induction motor drive. These techniques performed an automatic tuning strategy for the choice of the optimal parameters values and structures for the fuzzy controller. The computer simulations have been carried out to compare the new controllers performances to those of a PI-based controller [201].

Chan C.C. et al. reported an excellent speed control system for induction motor drives. Sliding mode control was employed to provide quick torque characteristics with robustness to motor parameter variations. The proposed system combines the precise speed regulation of PLL technique and the robustness of sliding mode control, with the insensitivity to disturbance and simulation results verified the validity of the system [202]. Harnefors L. and Hans-Peter Nee designed and analyzed a general algorithm for speed and position estimation of AC motors. They used a six-pole ELMO PMSM as test object and the control algorithms were implemented on a TMS320C40 floating point DSP [203]. Junji Y. et al described Fuzzy auto tuning based α-parameter ultimate sensitivity method for AC speed servo system. The effectiveness of the proposed autotuning control scheme in the ac speed servo system is verified in terms of computer simulation results [204]. Zhu Z. Q., Shen J. X. presented comparative study of alternative fuzzy logic control strategies of permanent magnet brushless AC motor drive. Their results showed application of fuzzy logic control to a vector controlled permanent magnet brushless AC motor drive exhibits better speed control performance than the PI control. A simple adaptive fuzzy logic control algorithm with self-tuned threshold speed error also proposed. It offered excellent speed control performance and robustness to parameter variations [205]. Sundareswaran K. reported a simplified model for speed control of AC voltage controller fed induction motor drives. He employed small
perturbation technique to derive linear incremental model of thyristorised ac voltage controller fed induction motor drive system and presented simulation results in comparison with the PI controller [206]. Morkani and Abdessemed proposed a novel design of a fuzzy-based self-tuning PI controller (FSTPIC) for speed control of an indirect field controlled induction motor. They studied performance of proposed controller under step and load variations. Simulation results showed that the fuzzy PI controller is better than the fixed gains one in terms of robustness and speed rise time and even under great variations of operating conditions and load disturbance [207].

2.7 Motivation for the present work

In view of the elaborated literature survey on application of fuzzy and integrated fuzzy logic controllers in the field of process control instrumentation, most of the research reported on the application of fuzzy and integrated fuzzy logic controllers for the process parameters control is based on simulation. Further, the design and real time implementation of fuzzy and integrated fuzzy logic controllers for process control is very rare. Even if so, it is not found in any research paper or report that the design of complete hardware (including DIOT card, 16-bit analog interface card and necessary signal conditioning and control circuitry) and development of software to realize fuzzy algorithms (using 'C' language) for measurement and control of a process parameter. For most of the applications MATLAB/ Simulink/ FuzzyTECH/ LabVIEW software and National Instruments' hardware have been used. Hence it is taken as the motivation for the present work and it focuses on the design and development of both the hardware and software aspects of computer based fuzzy and integrated fuzzy logic controllers (FLC and IFLC) for the process parameters such as DC motor speed, DC motor position, temperature, and AC motor speed. The present study emphasizes the complete design of the computer based control systems. The experimental work carried out in the present study is as follows,

1) The design and development of hardware includes
   - The design of compatible Digital Input/Output and Timer (DIOT) Card which includes two Programmable Peripheral Interfaces (8255A) and one Programmable Interval Timer (8254) for IBM PC.
• The design of 16-bit Analog Interface Card (AIC) includes 16-bit analog to digital converter (AD976), 8-channel analog multiplexer (DG508), and 16-bit digital to analog converter (AD7846).

These two cards, DIOT and AIC, have been designed as common cards for the measurement and control of four above-mentioned parameters.

• The design of hardware for DC motor speed control system (rated voltage 12V d. c., torque 50 gm-cm, and maximum speed 3000 RPM).

• The design of hardware for DC motor angular position control system (rated voltage 12V d. c., torque 750 gm-cm, and rated speed 50 rpm).

• The design of hardware for oven temperature control system (25 W, 0-90 °C range, 200 grams weight).

• The design of hardware for AC motor speed control system (230V/50Hz, single phase, power 1/15 HP, and rated speed 13000 RPM).

II) The design and development of software using ‘C’ language includes

• PID, Fuzzy and Integrated fuzzy logic controllers for
  • DC motor speed control system
  • DC motor position control system
  • Temperature control system and
  • AC motor speed control system

III) Study of the performance of above designed controllers for the following parameters,

• Set point variations
• Load variations and
• External disturbance (Noise) variations
REFERENCES


