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An In-depth Review of Fuzzy Logic Technique for Engineering Applications

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ABSTRACT

Fuzzy logic entails information of an unpredicted as opposed to Boolean logic. It is classed as an artificial intelligence technique to model and replace process control and designer/operator expertise. It offers competitive advantage over other methods in the industrial firms seeking technical-economic optimization. It is important to mention that, fuzzy logic does not necessarily replace the conventional control systems, rather it completes such systems. This study aimed at review of the most common fuzzy logic systems and their applications. The review was conducted through identification of current research in industry, agriculture and optimization of processes. Twenty five (25) papers were reviewed on four main areas: industrial application, agronomic application, crop husbandry application and optimization of process control systems. It was found out that fuzzy logic works best as effective feedback system in control systems. It is therefore, recommended for agricultural mechanization.

Keywords: *Neural network, optimization, automation, Microcontroller, fuzzy logic*

1. INTRODUCTION

Fuzzy logic simply refers to mathematical tool used in interpreting system decision. It reveals information as imprecise or tangled contrasts with Boolean logic, which simplifies the real world into two distinct categories: true or false (Singh *et al*., 2014). Fuzzy logic has become an operational technique in the modern day functions. It is used alongside with the advanced technique in industrial control and automation systems. It is important to mention that, fuzzy logic does not necessarily replace the conventional control systems, rather it completes such systems (Chevrie and Guely, 1998). Fuzzy logic is classed as an artificial intelligence technique to model and replace process control and designer/operator expertise. It offers competitive advantage over other methods in the industrial firms seeking technical-economic optimization (Chevrie and Guely, 1998). Fuzzy logic is mostly used in complex processes or where systems exhibit non-linear characteristics. Fuzzy logic also finds application where there are difficulties in using mathematical models to control plant development (Song, 2014). Different types of fuzzy controllers were proposed in literatures, and classified according to their structures as: PID (including PI and PD) controllers, types of membership function, types of fuzzy set, types of fuzzy logic system, fuzzy rules, method of defuzzification, application, reasoning models, degree of membership (Song, 2014). However, fuzzy PI controllers were used as controllers in control system applications to embrace classical or modern methods rather than solely

relying on linear PID controllers. The command used in the system was error measured between the reference variable and applied to actuator of a process. These types of controllers can find application in varying environments; but, required human expertise as they are model-dependent. The other category of fuzzy PD controllers are refers to heuristic control rules. However, most of the controllers used in research on fuzzy logic are in this category (Song, 2014). The structures of these controllers are analogous in nature used in input - output relationship.

The remaining sections of the paper are divided into five. Section 2 gives methodology of the research; section 3 detailed results and discussion, while section 4 highlighted future direction of the research and lastly section 5 give conclusion and recommendation

2. METHODOLOGY

The review was conducted through identification of current research in industry, agriculture and optimization of processes. The necessary materials were extracted and synthesized for the final step of review writing. A sum of 25 papers was compiled through searches across five databases; Elsevier, Semantic, Google Scholar, Research gate and Scopus. These five databases were chosen regarding the relevance of the research, it focuses on both the quality and quantity of articles retrieved from the searches. The majority of the chosen papers were published between 2014 and 2024, although some pertinent references may predate this timeframe.

The study aimed at review of the most common fuzzy logic systems and their applications. Four main review areas are: agronomic application, industrial application, crop husbandry application and optimization of the system. Research on fuzzy logic applications were queried using the keywords: “fuzzy logic in planting”, “seed drill based on fuzzy logic”, “seed spacing based on fuzzy logic”, “depth control based on fuzzy logic” and “optimization based on fuzzy logic”. Each paper chosen in this category included a structural diagram of the system. In an attempt to automate the process control of a particular system, control system and system inference need to be identified. The Meta-analysis on fuzzy logic application is shown in Table 1.

Table 1: Meta-analysis of Fuzzy Logic on engineering applications from recent literature

SN	Author	Year	Strength	Limitation
1	Singh *et al*.	2014	The review showed that fuzzy logic could find application in image processing, anaesthetic depth control, and optimization of water treatment system, industrial automation and drying process control of agricultural products.	It didn't cover planting operation, and other agricultural activities.
2	Samavat *et al*.	2023	They compared the Mamdani and Sugeno Fuzzy inference systems to determine best power of a PV system. It was however concluded that Sugeno controller showed a better performance over other controllers.	The study is limited to PV power control.
3	Melin and Castillo	2023	Assessed the ability of different controllers: type-3 fuzzy logic (T3FL) and the fractal dimension (FD) in addressing the problem of plant development monitoring.	The study only focused on plant growth.
4	Wang *et al.*	2018	Analyzed the shortage of the clustering algorithms and proposed a fuzzy-logic based energy-efficient clustering algorithm. The algorithm was evaluated via simulation software NS2. It was found out that it performs better than other clustering algorithm like LEACH and CHEF.	The study was only on energy efficiency and utilization.
5	Wang	2015	The study analyzed decision-making in industrial settings using Mamdani-type fuzzy inference system. Two membership functions: triangular and rectangular were used in researching a more controllable and reliable inference function. Triangular input MFs and rectangular output MFs were used, the linearity relationship in input-output was difficult to be achieved.	Consistency and reliability of the system was not ascertained.
6	Küçüktopçu *et al.*	2023	An artificial intelligence approach for the estimation of poultry weight based on fuzzy logic was proposed. Mamdani inferences system was used for decision making. The findings suggested that Fuzzy Logic method is more accurate and efficient poultry weight estimation.	Rectangular MFs was not used. System reliability and error were not tested.
7	Campos *et al.*	2023	The study compared fuzzy models, Mamdani and Sugeno to predict feed conversion in broilers. It shows that final result are affected by membership function and the defuzzification method. However triangular functions is best suited to Sugeno system while, Gaussian functions is better suited to the Mamdani.	Rectangular MFs was not used. System reliability and error were not tested.
8	Đurin *et al.*	2018	The study investigated the appropriateness of planting different agricultural crops using fuzzy logic was conducted. It aimed at reducing biases and subjectivities to the nearest minimum.	Depth of seeds placement was not investigated.
9	Katzer	2020	The study investigated fuzzy logic approach for small hydroponic systems. The system relied on the framework to be implemented in an (web) application and hence would run on any mobile device or computer.	The study was designed for crop propagation only.
10	Kim *et al.*	2022	Developed a fuzzy logic based system for cultivation of sweet basil.	It limited to crop propagation only.
11	Chang and Sie	2012	The study investigated the developmental growth of bionic botanical system using multistage fuzzy logic. Fuzzy logic inference and expert knowledge were jointly used to regulate the growth rate of the plants. It was concluded that the system developed could be used in automated plant cultivation system.	It limited to crop propagation only.
12	Truneh *et al*.	2021	A fuzzy logic based automatic plant watering system was investigated. There was no mathematical model used for all the parameters. Mamdani inference was employed as fuzzy control in the closed-loop. It was designed using MATLAB fuzzy logic toolbox.	It limited to automatic irrigation system only.

13	Yoseph *et al.*	2021	Reported on fuzzy logic on internet of things-based greenhouse. Fuzzy-Sugeno method was used to control the Greenhouse plant growth. A Long Range 915 Mhz was used in order to access the real-time situation of the plant development through Thingspeak server. Thingspeak server it is an application used in areas where internet network is difficult to be access.	It was limited to greenhouse temperature control.
14	Waluyo *et al.*	2022	Assessed the hydroponics and electrical energy consumption concerns based on fuzzy logic and the Internet of Things (IoT). The fuzzy-based method was found to increase the plant's height and growth rate, however, the energy consumption was lower than that of the scheduled-based method.	The control was only crop growth and energy consumption.
15	Chen *et al*.	2022	The study proposed a fuzzy logic based controller for adjusting the electrical conductivity and nutrient parameters. Electronic sensors were used in detecting the parameters while fuzzy controller was used for controlling the pump. It was concluded that the system could control the measured parameters effectively.	The study was limited to measure of electrical conductivity and nutrient parameters.
16	Qohar	2022	Study applied fuzzy logic in the optimization of photosynthesis and plant growth. It was found to be effective in keeping and controlling the photosynthesis time and plant growth.	It limited to photosynthesis and crop propagation only.
17	Li *et al.*	2020	The precise active seeding based on fuzzy PID in the control downforce system was reported. The study targeted to improve the soil compaction and the accuracy of setting working parameters. It replaces compressive spring mechanism with linear motor to control the downforce in real time. The detected force then serves as feedback for the fuzzy PID model. The system was able to adjust the system for different operating requirements.	It was limited to soil compaction only.
18	Li *et al.*	2021	The study designed an intelligent depth control system. They studied the sowing depth regulation system based on flex sensor and Mamdani fuzzy model for a no-till planter. The flex sensor monitors the downward force exerted by the seeding row unit against the ground while Mamdani fuzzy was used as intelligent regulation model. MATLAB-Simulink was used in simulating the working process of the system. It was concluded that Mamdani fuzzy model performed well in changing the pressure against ground.	The study was limited to depth of seed placement using flex sensor and Mamdani fuzzy model on a non-till planter
19	Liming *et al*.	2023	The study investigated sowing depth of seed placement and control system for no-till corn seeder using electro-hydraulic drive. They replaced mechanical drive mechanism with an electronic drive mechanism. The system was controlled through a PID control algorithm.	It is limited to depth of seed placement based on hydraulic drive.
20	Ji *et al*.,	2021	The study used Genetic Algorithm-optimized Back Propagation (GABP) algorithm and machine vision for the control of seed intra placement The system could reduce the seeding rate of the seeder and consistency of the seed spacing.	Limited to quantity of seed placed and seed spacing.

3. RESULTS AND DISCUSSIONS

3.0 APPLICATION OF FUZZY LOGIC

A review by Singh *et al*. (2014) on fuzzy logic and its applications was conducted. The authors studied its significance, structure and design of controller of fuzzy logic. The study showed that fuzzy logic could find its applications in image processing, anaesthetic depth control, and optimization of water treatment system, industrial automation and drying process control of agricultural products. However, some of the areas of fuzzy logic identified in engineering from review were: control systems, automotive systems, signal processing systems, biomedical engineering, robotics, consumer electronics, decision-making systems, optimization, pattern recognition. They are broadly grouped into three i.e. industrial application, agricultural application (agronomical and crop husbandry) and optimization.

3.1 Industrial Application of Fuzzy Logic

Samavat *et al*. (2023) compared the Mamdani and Sugeno Fuzzy inference systems to determine the best power of a PV system. The prototype controllers were designed and tuned by a genetic algorithm for the optimization of the controller. It was simulated in various radiations in MATLAB Simulink. It was however concluded that Sugeno controller performs better than other controllers. Melin and Castillo (2023) assess the abilities of type-3 fuzzy logic (T3FL) and the fractal dimension (FD) in solving problem of monitoring a plant. Wang *et al.* (2018) analyzed the shortage of the clustering algorithms and proposed a fuzzy-logic based energy-efficient clustering algorithm. The algorithm was evaluated via simulation software NS2. It was found out that it performs better than other clustering algorithm like LEACH and CHEF.

In 2015, Wang reported on utilizing membership functions within the Mamdani fuzzy inference system for industrial decision-making applications. The study aimed engaging in research to explore the Mamdani fuzzy inference process and develop methods to enhance system stability. Triangular membership functions were employed for input, while rectangular membership functions were utilized for output. Achieving linearity in the input-output relationship proved challenging. An artificial intelligence approach for the estimation of poultry weight based on fuzzy logic was proposed by Küçüktopçu *et al.* (2023) as a viable solution. Mamdani inferences system was used for decision making. The findings suggested that Fuzzy Logic methods hold performs best in poultry weight estimation. Campos *et al.* (2023) compared fuzzy models, Mamdani and Sugeno to predict feed conversion in broilers. The comparison between models revealed that the choice of membership function type and the defuzzification method significantly impact the final outcome. It was concluded that, triangular functions is best suited to the Sugeno system while, Gaussian functions is best suited to the Mamdani system for all defuzzification methods.

3.2 Agricultural Application of Fuzzy Logic

3.2.1 Agronomic application of fuzzy logic

Neural network has various applications in the agricultural activities (Zhu *et al.*, 2018) such as seeding spacing (Ji *et al*., 2021), ditching (Chen *et al*., 2022), cost estimation of repair and maintenance of rice combine (Numsong *et al*., 2023) and other functions. Neural networks, also known as artificial neural networks (ANNs), are information processing

systems structured akin to the human brain, capable of learning from observations and generalizing through abstraction (Song, 2014). They are often trained to recognize complex, nonlinear relationships within data and find application in various domains including control systems, biomedical engineering, pattern recognition, and speech processing. Unlike traditional mathematical models such as regression or PID controllers, ANN models possess the ability to self-tune. This characteristic enables them to make decisions autonomously in response to unusual perturbations, disturbances, or changes in environmental conditions (Song, 2014). Neuro-fuzzy systems, on the other hand, employ neural network techniques within fuzzy technology frameworks.

Exploring the suitability of cultivating diverse agricultural crops through the application of fuzzy logic was conducted by Đurin *et al.* (2018). It aimed at reducing biases and subjectivities to the nearest minimum. Katzer (2020) investigated fuzzy logic approach for small hydroponic systems. The system relied on the framework to be implemented in an (web) application and hence would run on any mobile device or computer. Kim *et al.* (2022) developed a fuzzy logic based system for cultivation of sweet basil. The developmental growth of bionic botanical system using multistage fuzzy logic was reported by Chang and Sie (2012). Fuzzy logic inference and expert knowledge were jointly used to regulate the growth rate of the plants. It was concluded that the system developed could be used in automated plant cultivation system. Submission by Truneh *et al.*, (2021) on automatic plant watering system based fuzzy logic, given the absence of mathematical models for all parameters, the fuzzy logic technique emerges as the most suitable choice for modeling, as it mimics human brain behavior more closely. Subsequently, the Mamdani inference algorithm was utilized as the fuzzy control model for this closed-loop control system. The controller was designed using MATLAB fuzzy logic toolbox. Yoseph *et al.* (2021) reported on implementing fuzzy logic in an Internet of Things (IoT)-enabled greenhouse. The Fuzzy-Sugeno method was employed to regulate greenhouse temperature, pH levels, and soil moisture to facilitate optimal plant growth. A Long Range 915 Mhz was used in order to access the real-time situation of the plant development through Thingspeak server. Thingspeak server it is an application used in areas where internet network is difficult to be access. In the early 2022, Waluyo *et al.* (2022) addressed hydroponics and electrical energy consumption issues through the integration of fuzzy logic and the Internet of Things (IoT). The control component utilized an Arduino Mega 2560 microcontroller board. The fuzzy-based approach was observed to enhance plant height and growth rate, while simultaneously reducing energy consumption compared to the scheduled-based method. Chen et al. (2022) proposed a utilizing a fuzzy logic controller to regulate the electrical conductivity and pH levels of the nutrient solution within a hydroponic system. Electronic sensors were employed to detect these parameters, while the fuzzy controller managed the pump operation. For input and output control, a Raspberry Pi3 development board was utilized. The fuzzy control program was developed using the Geany development environment on the Raspberry Pi3, written in the C language. Pin settings were configured using the bcm2835 library, as Python pins were not utilized due to the requirement of g++ for handling general-purpose input/output (GPIO) pins. The system demonstrated

effective control over the measured parameters. Additionally, Qohar (2022) applied fuzzy logic for optimizing photosynthesis and plant growth, achieving effective control over photosynthesis duration and plant growth.

3.2.2 Crop husbandry application of fuzzy logic

The control system for downforce based on fuzzy PID was reported by Li *et al*. (2020). The study aimed to enhance soil compaction and precision in setting operational parameters. To achieve this, a linear motor replaced the compressive spring mechanism to enable real-time control of downforce. A force sensor, connected in series with the linear motor, detected the actual downforce exerted by a press wheel on the soil, providing feedback for the fuzzy PID model. It was concluded that the system effectively adjusted operating requirements such as soil stiffness, moisture levels, and crop species.

In another study, Li et al. (2021) developed an intelligent depth control system for a no-till planter. They utilized a flex sensor to monitor the downward force exerted by the seeding row unit against the ground and implemented a Mamdani fuzzy model for intelligent regulation. MATLAB-Simulink was employed for simulating the system's operation, with the Mamdani fuzzy model demonstrating proficient performance in adjusting pressure against the ground.

In a separate investigation by Liming et al. (2023), the focus was on sowing depth control for a no-till corn seeder using an integrated electro-hydraulic drive. They replaced the mechanical drive mechanism with an electronic drive mechanism and implemented a PID control algorithm for system control. However, there are currently no published reports on the application of a fuzzy logic-based controller for linear displacement sensor and proximity sensor control.

3.3 Optimization Process based on Fuzzy Logic

The optimization of gradient-based techniques involves determining search directions to minimize an objective or error function. This approach was applied to minimize material loss in the control system while maintaining precision accuracy (Ji et al., 2021). Commonly utilized techniques include Genetic Algorithms (GAs), simulated annealing, random search, and the downhill simplex method. These techniques mimic natural genetic principles and diverge from traditional search and optimization methods employed in engineering design problems. By borrowing fundamental concepts from genetics and artificially constructing search algorithms, these techniques exhibit robustness and require minimal problem-related information.

Ji et al. (2021) utilized the Genetic Algorithm-optimized Back Propagation (GABP) algorithm alongside machine vision for controlling seed planting positions in precision farming. The intelligent system demonstrated the ability to reduce seeding rates and improve the consistency of seed spacing.

4.0 FUTURE RESEARCH DIRECTION

The future research direction on agricultural application will be majorly on automating agricultural production and its services; such as: crop husbandry, crop protection, harvesting and postharvest operations. It is therefore our intent to embark on automating planting operation.

5.0 CONCLUSION

A review study on the application of fuzzy logic was conducted, exploring three main areas: industrial, agricultural and optimization. The findings suggest that fuzzy logic proves most effective as a control

system, particularly in automation and control systems, warranting its recommendation for use in such applications.

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