Comparative Performance of Mamdani and Sugeno Fuzzy Logic Control Systems in Governing the Motion of a Robotic Arm

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Abstracts: In this research, a simulation study of a prototype medical robotics system was conducted to evaluate the performance of Mamdani and Sugeno fuzzy logic control systems in response to varying Step Input values. The Mamdani control system demonstrated faster response times and better adherence to setting time in the absence of disturbances. However, the Sugeno system outperformed Mamdani in scenarios where overshoot percentage was a critical factor. Even in the presence of disturbances, Mamdani maintained faster response times, lower Risetime, and minimal or no overshoot. Nevertheless, Mamdani's setting time responses were sometimes similar to or slower than Sugeno, which may be attributed to Mamdani's higher fuzziness compared to Sugeno's more linear nature. In conclusion, Mamdani exhibited superior speed and adherence to setting time when overshoot percentage was not a critical factor. Furthermore, Mamdani's higher fuzziness, compared to Sugeno's linearity, may explain the observed differences in responses between the two fuzzy logic control systems.

Keywords: MATLAB/Simulink, Robotic Arms, Trajectory Control.

1. INTRODUCTION

Nowadays, medical robotics plays an increasingly crucial role in various aspects of human daily life, including healthcare, restaurants, hotels, factories, and hazardous environments. The integration of robotics minimizes long-term risks for humans, particularly in handling diverse chemical substances. Continuous advancements in hardware, software, and control systems across various technologies have facilitated rapid progress in this field.

MATLAB/Simulink is a program [1]-[4] widely recognized for its capabilities in algorithm development, mathematical model creation, and system simulation. Research studies have presented comparative methods, outlining the advantages and disadvantages of different control systems, such as the PI control, PID [5]-[8], which is a basic control system design that is easy to implement but often faces challenges with excessive overshooting. Another example is the fuzzy logic control system [9]-[15], which combines PID and fuzzy logic to address overshooting issues using fuzzy logic to adjust system overshoot. Additionally, artificial neural networks [16] have been employed to design system overshoot for optimal output signal approximation, but face challenges related to the amount of data required for learning.

In designing the aforementioned control systems, creating a model for system development is crucial. The modeling process is vital for estimating simulation results before practical implementation. Simulation studies in various research have limitations in modeling batch process system functions, which cannot be written into normal function programs using matrix system P equations [17]. This is where the MATLAB and Simulink programs come into play, enabling the control and simulation of medical robotic arm control systems.

This research introduces the design of Mamdani and Sugeno fuzzy logic control systems for approximation in fuzzy logic control systems to compare their performance in normal and disturbed signal scenarios. Furthermore, the study compares their performance with different step input signals, specifically at 20 and 60 degrees, to assess adaptability within varying signal ranges, flexibility, and robustness in control signal design. Additional aspects of this research will be presented in the following sections.

2. PROTOTYPE MEDICAL ROBOTIC ARM

2.1. Medical Robotics Structure

According to Figure 1, the prototype medical robotic arm used in this research was presented in the study by Chotikunnan P. and colleagues [17]-[19]. The robotic arm features a motorized structure allowing movement in various directions with three axes of motion, represented by joints A, B, and C. Joint A serves as the pivot point of the robotic arm, joint B is responsible for the up-and-down motion, and joint C controls the sweeping angle of the robot. The control processing system, executed by MATLAB/SIMULINK software and an Arduino board, receives feedback through adjustable resistors to monitor the movement angles at each joint.

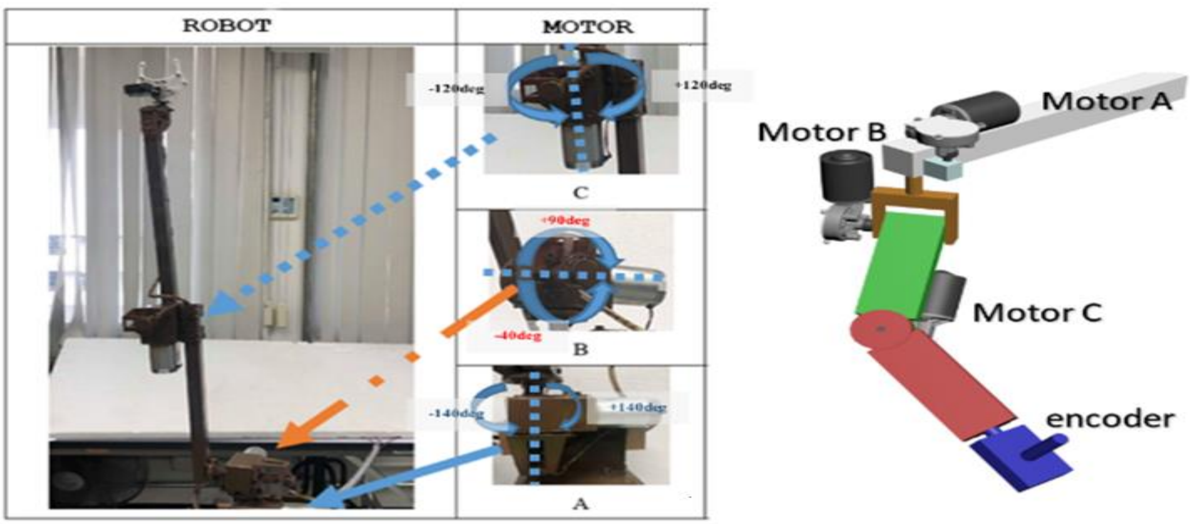

Figure 1. Robotics arm system

The equations governing the motion of the prototype medical robotic arm were formulated through simulation, taking into account the input and output signals within the designated time domain. The researcher characterized the repetitive robotic motions for each axis, assuming a discrete-time and randomly sampled system with a sampling time of 0.055 seconds. This approach enables the approximation of the transfer function depicted in equation (1), encompassing all motors. The system identification process was implemented using MATLAB, and the associated parameters are detailed in Table 1.

$$G(z) = \frac{\gamma z}{z^2 + \alpha z + \beta} \tag{1}$$

Where the value of $G(z)$ represents the system equation of the robotic arm, with the coefficients γ, α, β given in Table **1.**

Table 1. Displays the parameters of the motors utilized in the OPEN-LOOP system

	γ	α	β
MOTOR A	0.072800	-1.423520	0.423020
MOTOR B	0.065985	-1.416977	0.416566
MOTOR C	0.059974	-1.420447	0.420346

3. CONTROL SYSTEM DESIGN

In this section, the discussion revolves around the design of a phase-locked control system for managing the motion of motors in the robotic arm along each axis. The system incorporates two input signals. Input 1 signifies the system's error signal and is governed by a set of 5 rules. Input 2 corresponds to the derivative of the error signal and is also regulated by a set of 5 rules. The permissible range for both input signals is -40 to 40 units, while the output adheres to a set of 9 rules and is confined within -100 to 100. The design is elucidated in Figure 2, a Simulink diagram portraying the comprehensive operation of the simulation program. Sub Systems for motors A, B, and C are delineated in Figures 3-5. The system simulation incorporates scenarios with and without disturbance signals, introduced through the Band-Limited White Noise Block, illustrated in Figure 6. The noise power is set at 0.0025, and Table 2 provides an overview of the Membership Functions of the system. The fuzzy logic control system employs Mamdani and Sugeno processing methods, as evident in the simulation program depicted in Figure 2.

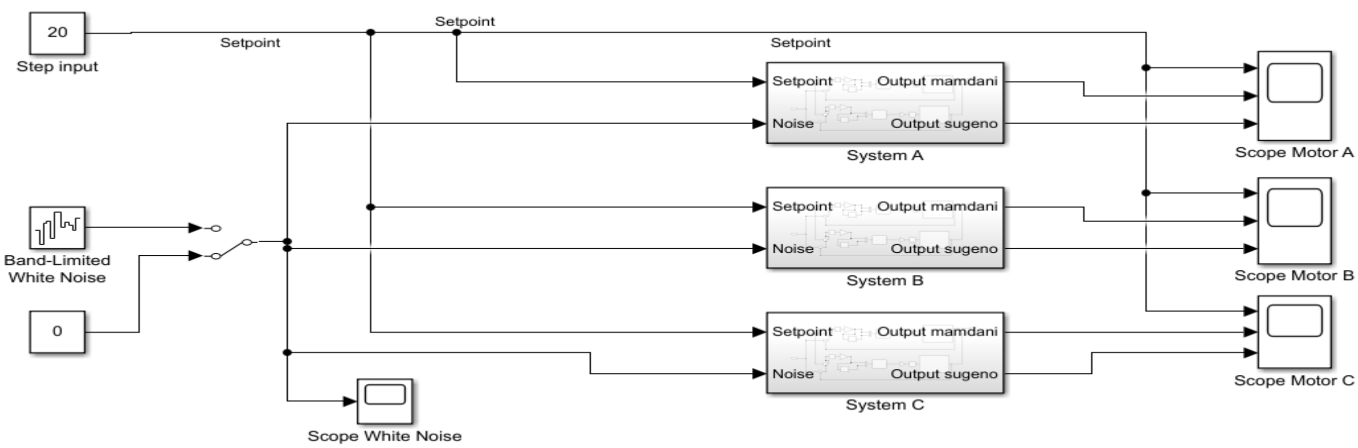

Figure 2. Schematic drawing Simulink of robotics arm system.

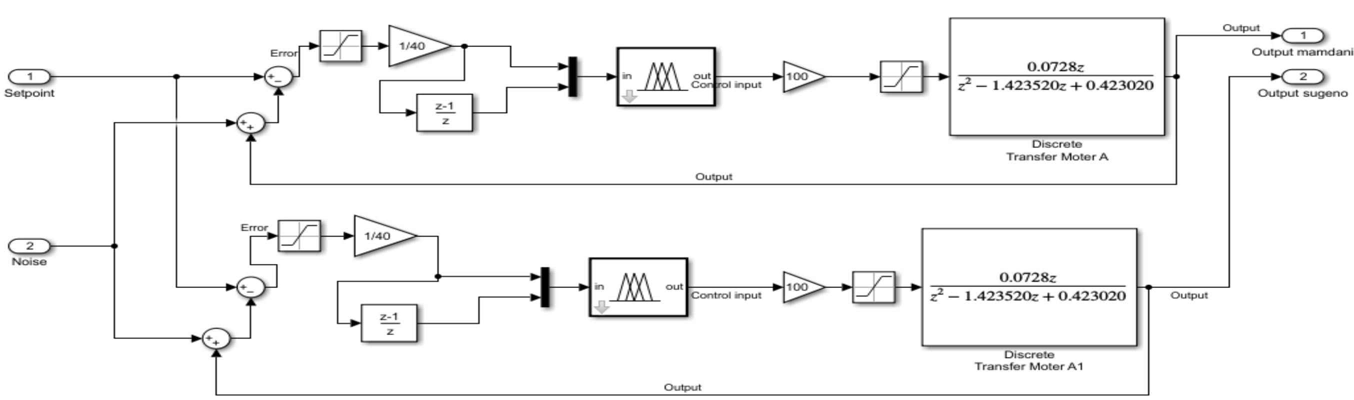

Figure 3. Subsystem of motor A.

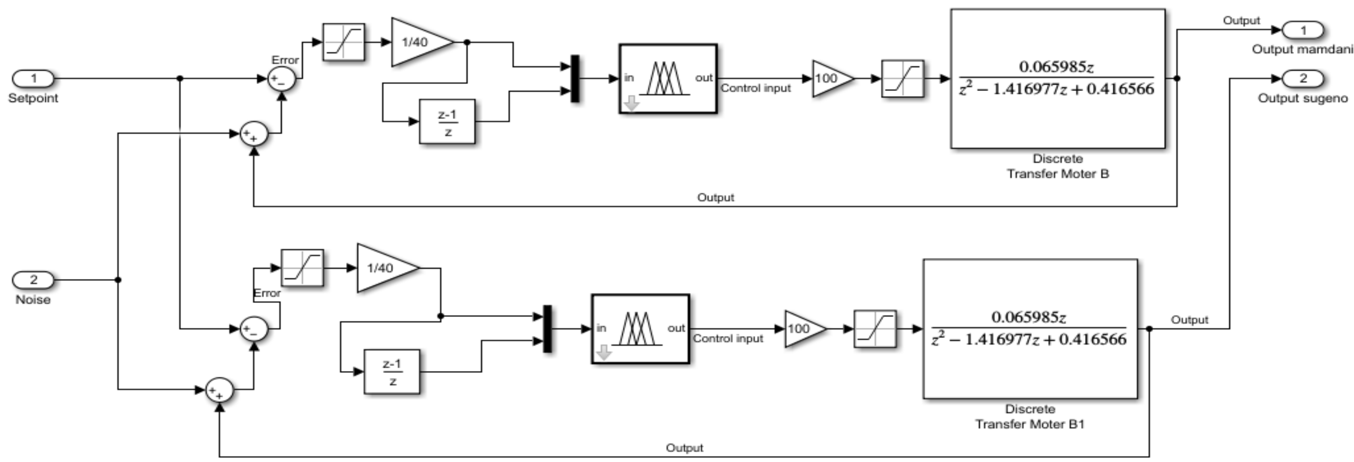

Figure 4. Subsystem of motor B.

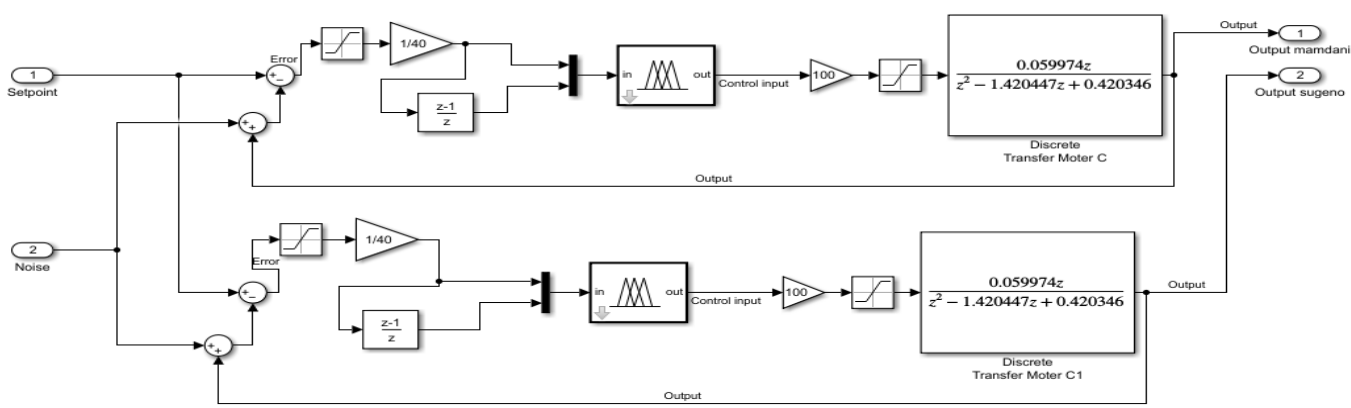

Figure 5. Subsystem of motor C.

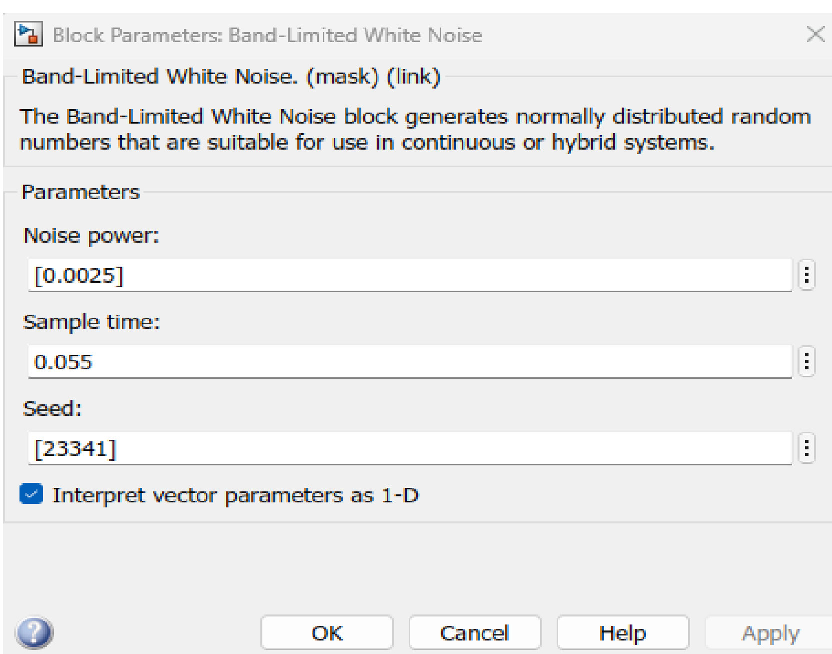

Figure 6. Band limited white noise block.

Table 2. The table presents the membership functions

		INPUT 1				
		NB	**NS**	**ZO**	**PS**	**ZP**
INPUT 2	**NB**	VNB	NB	PB	PB	VPB
	NS	NB	NM	PS	PM	PB
	ZO	NM	NS	ZO	PS	PM
	PS	NB	NM	NS	PM	PB
	PB	VNB	NB	NB	PB	VPB

3.1. Mamdani-Type Fuzzy Logic Control System

In this section, the discussion revolves around the design of a Mamdani-type Fuzzy Logic Control System, as illustrated in Figure 7. The design incorporates Input 1, representing the system's error signal, governed by a set of 5 rules outlined in Figure 8. Input 2 corresponds to the derivative of the error signal and is controlled by a set of 5 rules as depicted in Figure 9. The output is subject to a total of 9 rules, with a signal range spanning from -100 to 100, as visually represented in Figure 10. Furthermore, the relationship between Membership Functions is portrayed through surface plots, providing a visualization of the estimated response values derived from the equation using the Mamdani method, as presented in Figure 11.

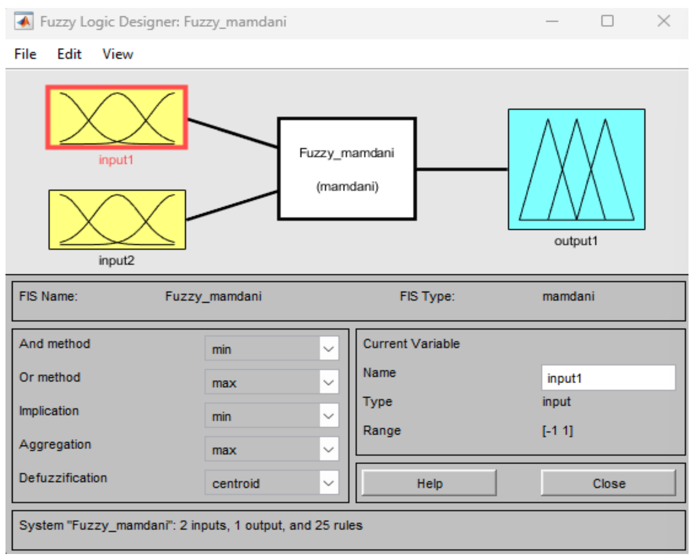

Figure 7. Fuzzy logic designer of Mamdani-type.

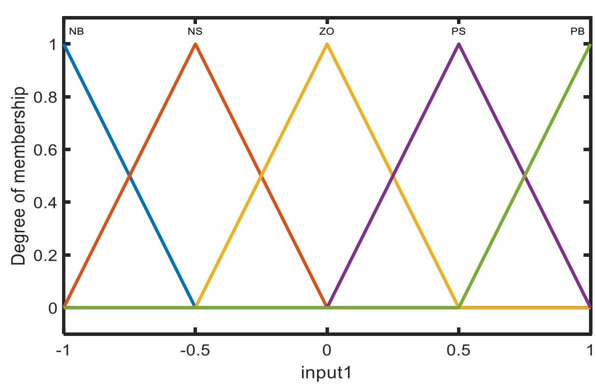

Figure 8. Membership function of Mamdani-type for input 1.

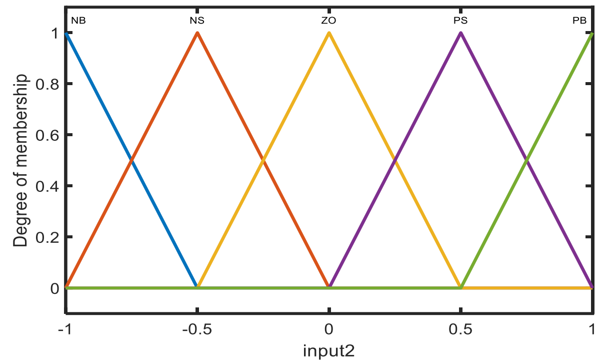

Figure 9. Membership function of Mamdani-type for input 2.

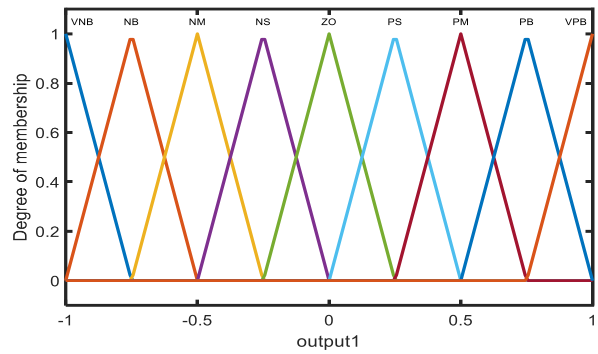

Figure 10. Output membership function of Mamdani-type.

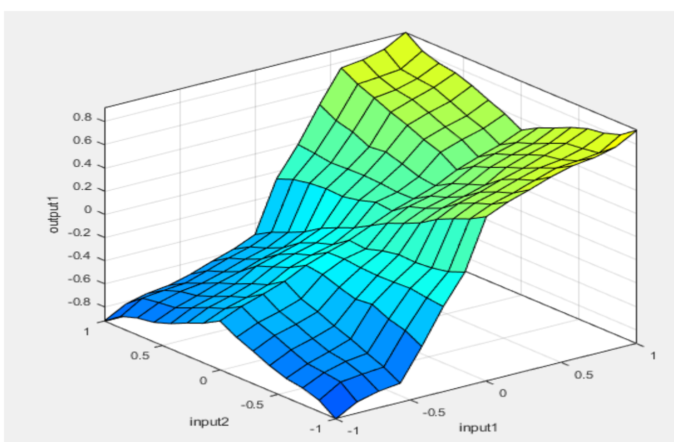

Figure 11. The surface plots depict the estimated response values of the equation approximated using the Mamdani method.

3.2. Sugeno-Type Fuzzy Logic Control System

In this section, the discussion focuses on the design of a Sugeno-type Fuzzy Logic Control System, as depicted in Figure 12. The design encompasses Input 1, representing the system's error signal, controlled by a set of 5 rules outlined in Figure 13. Input 2 corresponds to the derivative of the error signal and is subject to a set of 5 rules, as illustrated in Figure 14. The output is governed by a total of 9 rules, with a signal range set between -100 to 100, as shown in Figure 15. The relationship between Membership Functions is visually represented through surface plots, depicting the estimated response values of the equation approximated using the Sugeno method, as presented in Figure 16.

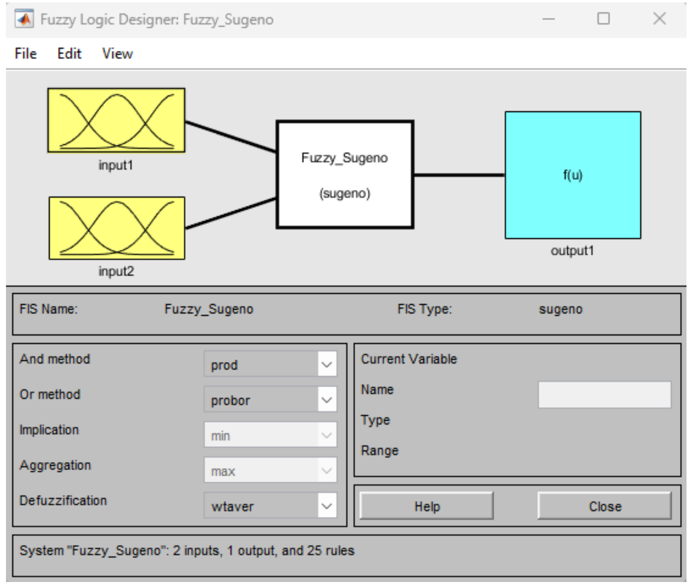

Figure 12. Fuzzy logic designer of Sugeno-type.

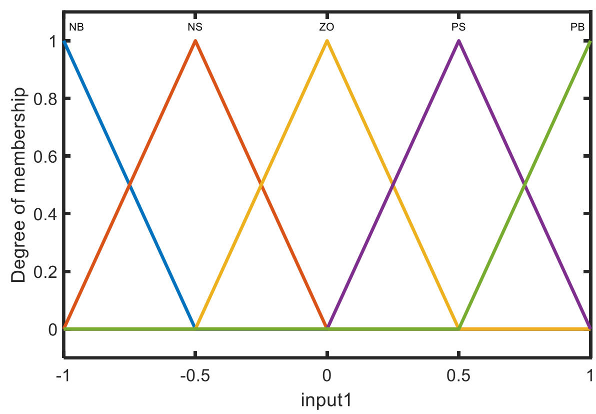

Figure 13. Membership function of Sugeno-type for input 1.

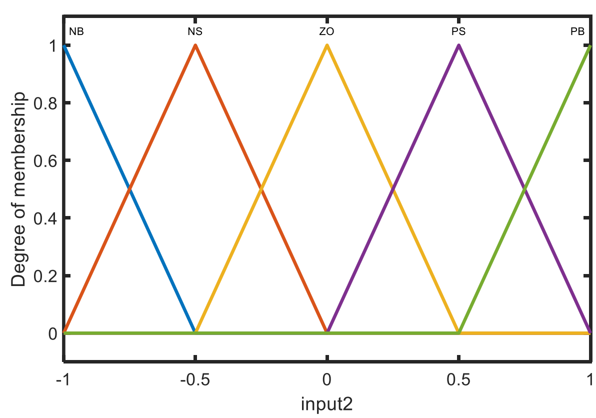

Figure 14. Membership function of Sugeno-type for input 2.

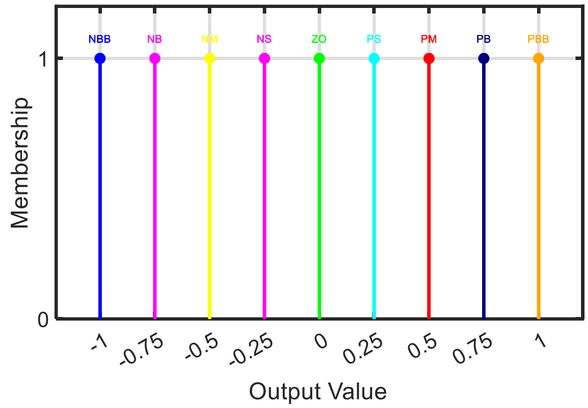

Figure 15. Output membership function of Sugeno-type.

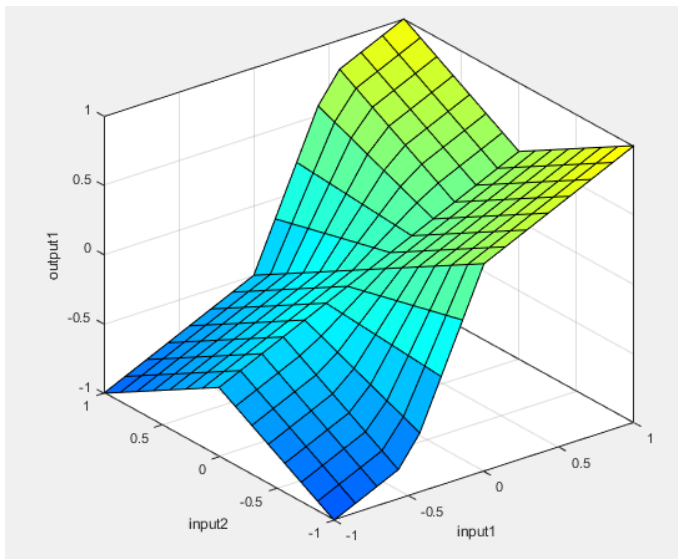

Figure 16. The surface plots depict the estimated response values of the equation approximated using the Sugeno method.

4. THE SIMULATION RESULTS OF THE PROTOTYPE MEDICAL ROBOTIC ARM SYSTEM

In simulating this system, examples of operations at joints A, B, and C are demonstrated, setting Step Input values for parameter testing at 20 and 60 degrees, respectively. The simulations are conducted both without disturbance signals and with disturbance signals.

In the experiment with Step Input set at 20 degrees, which is below the input design boundary in fuzzy logic rules, the Mamdani-type fuzzy logic system exhibits a rapid system response. The Risetime of the system is lower compared to the Sugeno-type fuzzy logic system. Regarding reaching the system's setting time, the Mamdani-type system shows a slightly smaller percentage of overshoot (%OS), while the Sugeno-type system exhibits no %OS in its response. The setting time values for both systems are closely aligned, as depicted in Figure 17, representing the results of the simulation for joints A, B, and C.

Similarly, in the experiment with Step Input set at 60 degrees, which is still below the input design boundary in fuzzy logic rules, the Mamdani-type fuzzy logic system demonstrates a rapid system response. The Risetime of the system is lower compared to the Sugeno-type fuzzy logic system. Regarding reaching the system's setting time, the Mamdani-type system shows either a significantly lower %OS or none, while the Sugeno-type system exhibits no %OS in its response. The setting time values for both systems are closely aligned, as depicted in Figure 18, representing the results of the simulation for joints A, B, and C.

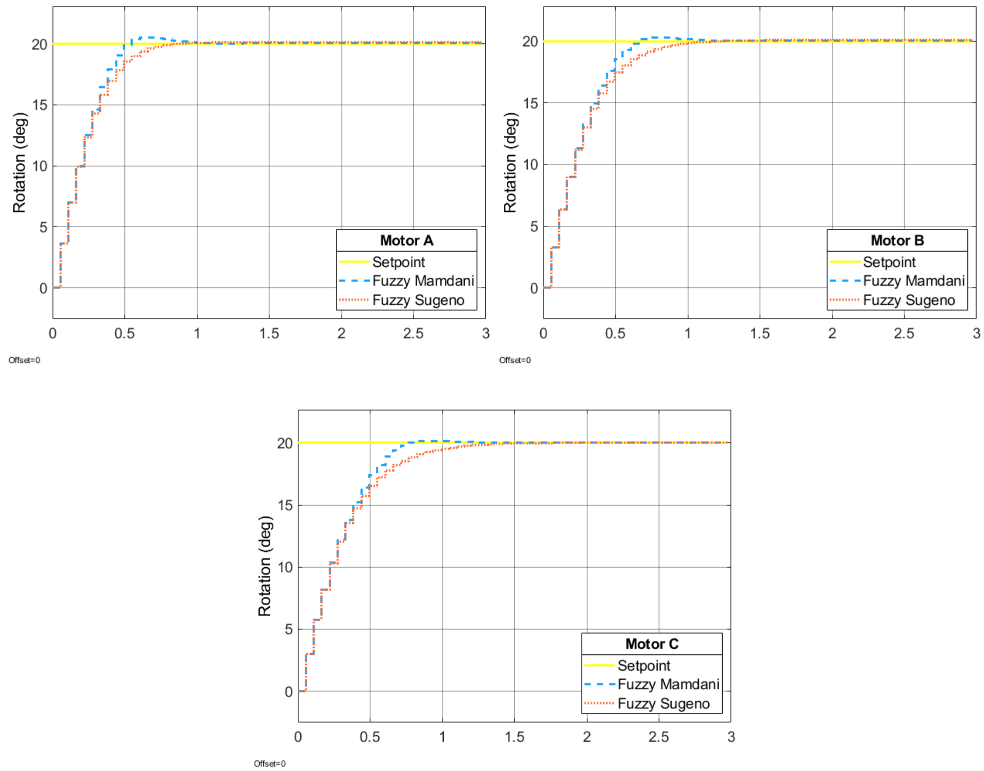

Figure 17. Illustrates the system response results with a setpoint value of 20 degrees and no disturbance signals introduced into the system.

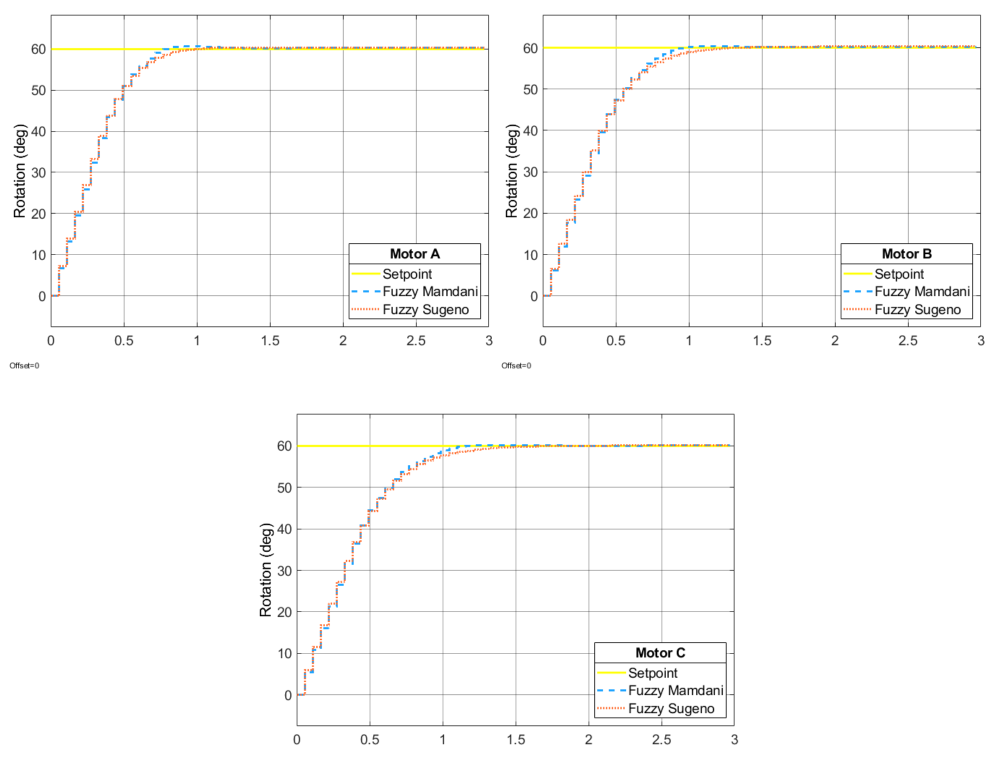

Figure 18. Displays the system response results with a setpoint value of 60 degrees and no disturbance signals introduced into the system.

By simulating the system with Step Input values set at 20 and 60 degrees, and introducing disturbance signals, the system response is observed to be similar to the operation in the absence of disturbances. However, the Mamdani-type fuzzy logic system may exhibit more significant changes in system response compared to the Sugeno-type, with the Mamdani-type system showing a faster system response. The Risetime of the system is lower than the Sugeno-type, and when reaching the system's setting time, the Mamdani-type system exhibits significantly lower or no percentage of overshoot (%OS), while the Sugeno-type system shows no %OS in its response. The setting time values for both systems are closely aligned, as depicted in Figures 19 and 20, representing the results of the simulation for joints A, B, and C.

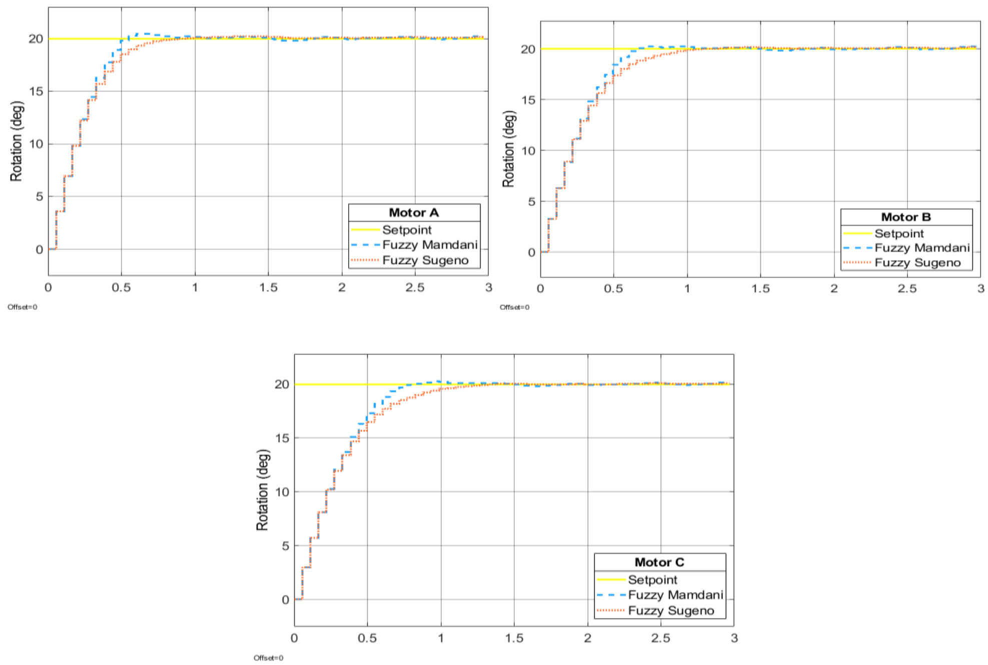

Figure 19. Depicts the system response results with a setpoint value of 20 degrees and the introduction of disturbance signals into the system.

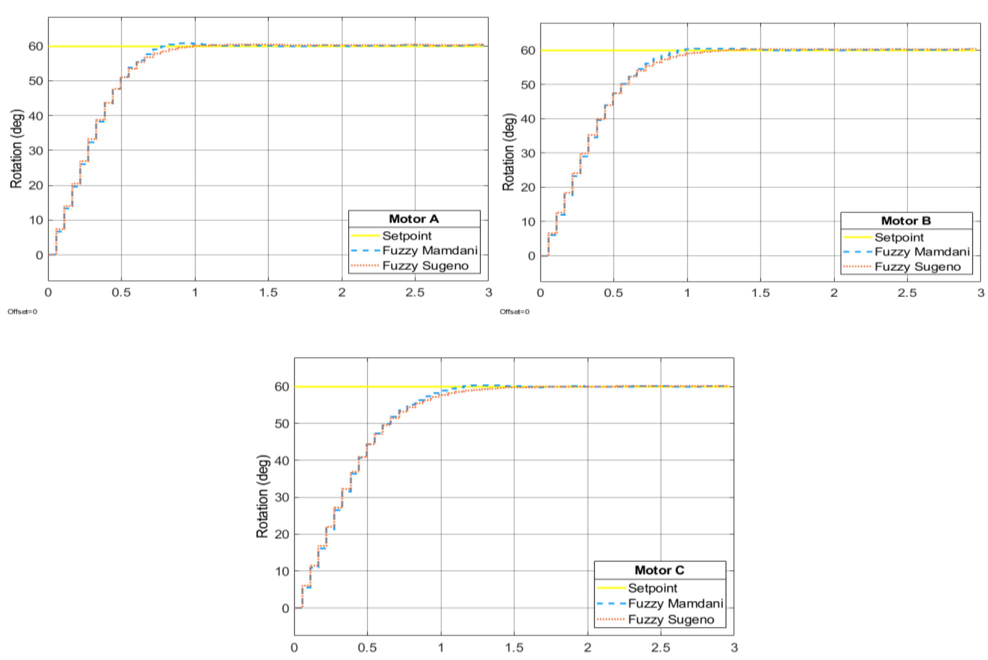

Figure 20. Illustrates the system response results with a setpoint value of 60 degrees and the presence of disturbance signals in

the system.

In summary, the Mamdani-type fuzzy logic control system demonstrates a better performance in achieving the system's setpoint within the desired setting time compared to the Sugeno-type fuzzy logic control system. However, in terms of overshoot percentage within the system, Sugeno outperforms Mamdani. Mamdani, if within the specified rule boundaries, can provide optimal and efficient system operation. However, if it exceeds these boundaries, the Mamdani system may exhibit a delayed response or provide similar system responses. This difference may be attributed to the higher fuzziness nature of the Mamdani system compared to the more linear nature of the Sugeno system, as evident from the surface plots in Figures 11 and 16.

CONCLUSIONS

In the simulation study of the prototype medical robotics system, the results highlight the impact of Mamdani and Sugeno fuzzy logic control systems on the response to different Step Input values. The Mamdani control exhibits faster response and better adherence to the setting time compared to the Sugeno system when there is no disturbance. However, Sugeno outperforms Mamdani when the overshoot percentage is crucial. Even in the presence of disturbances, Mamdani maintains a faster response, lower risetime, and minimal or no overshoot. Nevertheless, Mamdani's setting time may exhibit responses similar to or slower than Sugeno. This difference may stem from Mamdani's higher fuzziness compared to Sugeno's more linear nature. In conclusion, Mamdani demonstrates superior speed and adherence to setting time when the overshoot percentage is not critical. Furthermore, Mamdani's higher fuzziness compared to Sugeno's linearity might explain the observed differences.

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