CHAPTER 4
FUZZY LOGIC FOR NETWORKED
DC MOTOR CONTROL

The PID control algorithm has been widely applied to many control systems of industry manufacturing processes to solve efficiently the control problems of manufacturing processes because of its good adaptability and simple technology. However, PID control algorithm is a kind of delay control and which also requires the precision mathematical model for the control systems. When the control process is that of very complex, it is associated with uncertainty. In this case, the PID control algorithm cannot realize the real time control and the control accuracy is limited. Thus it is difficult to increase the quality of the control system further. As an improved control algorithm, the fuzzy logic control has been proposed for the networked DC motor control in this chapter.

4.1 INTRODUCTION TO FUZZY LOGIC CONTROLLER

Fuzzy inference systems have been successfully applied in various fields such as computer vision, decision analysis, data classification, expert systems and automatic control. Because of the multidisciplinary nature, fuzzy inference systems are associated with a number of names, such as fuzzy expert systems, fuzzy-rule based system, fuzzy associative memory, fuzzy modeling, simply fuzzy systems and fuzzy logic controllers (FLC).

Fuzzy logic controller describes the algorithm for control systems as a fuzzy relation between information on the condition of the process to be
controlled and the control action. It is distinguished from conventional control system since only information about the system is required rather than as a precise mathematical model for a conventional control system. The assumption generally made in fuzzy logic control is that the plant is observable and controllable and the input/output variables are available for observation and measurement or computation.

There are four main modules in the fuzzy logic controller as fuzzification module, knowledge base, fuzzy inference engine and defuzzification module. The physical values of the process state variables are mapped into a normalized universe of discourse and perform fuzzification which converts a pointwise, crisp value of a process state variable into a fuzzy set in order to make it compatible with the fuzzy set representation of the process state variable in the rule antecedent. The knowledge base module consists of a database and a rule base. The function of the database is to provide the necessary information for the proper functioning of the fuzzification module, the rule base and the defuzzification module.

The information includes the fuzzy sets representing the meaning of the linguistic values of the process state and control output variable. The design parameters are the choice of membership functions and the choice of scaling factors. The function of the rule base is to represent the structured control policy of an experienced process operator in the form of a set of production rules if process states then control output. The design parameters include the following

- Choice of process state and control output variables
- Choice of the contents of rule consequent and the rule antecedent
• Choice of the range of linguistic values for the process state and control variables and

• Finally the derivation of the set of rules.

There are two basic types of approaches in the design of the inference engine of FLC as composition based inference and individual rule based inference. The design parameters for the inference engine are choice of representing the meaning of single production rule, choice of representing the meaning of the set of rules, choice of inference engine and testing the rules for consistency and completeness.

The defuzzification module performs the conversion of the aggregated fuzzy values to a crisp value and the mapping of the pointwise value of the control output to the physical domain or the real world. The various steps involved in the design of a fuzzy logic controller are

1. Identify the inputs and outputs using linguistic variables.

2. Assign membership functions to the variables.

3. Build a rule base or derive the relationship between the input and the output variables.

4. Choose appropriate scaling factors for the input and output variables.

5. Fuzzify the inputs, use fuzzy approximate reasoning to infer the output contributed by each rule, aggregate the fuzzy outputs and apply defuzzification to form a crisp output.

There are two types of implementing the fuzzy systems in the MATLAB toolbox as Mamdani-type and Sugeno-type.
4.2 NETWORKED DC MOTOR CONTROL USING FUZZY MODULATED PID (FMPID) CONTROLLER

The Fuzzy Logic Controller (FLC) is used as Fuzzy Modulator. Basically the FLC consists of three parts as fuzzifier that converts the error signal into linguistic values, inference engine that creates the fuzzy output using fuzzy control rules generated from expert experience and defuzzifier that calculate the control input to the plant from the inferred results.

It is known that the network delays ($\tau_{ca}$ and $\tau_{sc}$) and the losses of data will affect the network-based system by increasing the value of the control signal $U_{pid}(t)$ provided by the PID controller. The control signal $U_{pid}(t)$ is dependent on the error signal $e(t)$, which is dependent on the measured output $y_r(t)$ coming from the remote site via the network. So, at the beginning $e(t)$ will be large, which leads to the large control signal $U_{pid}(t)$. However, as output $y(t)$ approaches $r(t)$, (i.e), $e(t) \approx 0$, there are network delay and loss that the PID controller realize that the control signal should be decreasing. Depending on the delay and loss the $U_{pid}(t)$ will keep increasing, which will lead $y(t)$ increase to a higher value. Thus, $e(t)$ will be higher than before which leads $U_{pid}(t)$ to keep increasing. This network challenges effect, can lead to unstable closed loop system response. Thus in order to compensate this effect to the network challenges on the controlled dc motor without completely redesigning the controller.

The block diagram of the FMPID controller for networked controlled DC motor is shown in Figure 4.1.
Figure 4.1 FMPID controller for networked DC motor control

To compensate and improve the performance of the PID controller under different network delays and losses, a parameter $\beta$ is introduced as in Equation (4.1) such that the control signal provided by the controller is

$$U_c(t) = \beta U_{PID}(t)$$  \hspace{1cm} (4.1)

where $U_c(t)$ is the modulated version of the control signal provided by the central PID controller with parameter $\beta$. The compensation parameter $\beta$ is given by equation (4.2)

$$\beta = h_f(e(t), u(t))$$  \hspace{1cm} (4.2)

where $h_f$ is a nonlinear function that describes the input/output relation of the fuzzy compensator.
The fuzzy modulator receives the input as the error signal $e(t)$ in addition to the output from the PID controller $U_{PID}(t)$. Thus based on the performance of the networked DC motor with respect to challenges, the fuzzy compensator is composed of the rules as

If $e(t)$ is small and $U_{PID}(t)$ is large, then $\beta$ is $\beta_1$

If $e(t)$ is large and $U_{PID}(t)$ is large, then $\beta$ is $\beta_2$

And in order to achieve the desired output the condition as $\beta<\beta_1<\beta_2<1$ where $\beta_i$, $i=1,2$ are the consequent parameters corresponding to the modulation parameter $\beta$.

The fuzzy modulator model design contains two input and one output linguistic variables. The input linguistic variables are error signal and PID controllers output signal and the output linguistic variable is the modulated parameter. Two membership functions associated with the input variables are small and large. The membership function parameters are tuned off-line. The coefficients of the membership functions are determined by several trial and error experiments with the plant and without the network. For faster execution of the fuzzy logic controller, the Mamdani’s min-max inference method and the central average defuzzifier are used.

The fuzzy modulated PID controller produces the control signal $U_c(t)$ is transmitted to the remote plant and the output $y(t)$ speed of the motor is transmitted to the controller via network where delay and losses of data might occur. Depending on the error signal received at controller, the control signal is produced to compensate the network challenges and improve the performance of the system.
4.3 SIMULATION RESULTS WITH FMPID CONTROLLER

In this section, the networked DC motor is controlled using Fuzzy modulated PID controller and the simulation results are compared with PID controller. The simulation model of the system with FMPID is shown in Figure 4.2. To demonstrate the effectiveness of the fuzzy modulated PID controller for networked DC motor, we choose $\beta_1 = 0.2$ and $\beta_2 = 0.25$ and the simulation results are shown in the Figures 4.3 to 4.10.

![Simulation model of the system with FMPID controller](image)

**Figure 4.2 Simulation model of the system with FMPID controller**

Figure 4.3 shows the system performance using FMPID and PID controller without delay and losses. In Figure 4.3 it can be seen that PID controller response has 13.3% overshoot and the settling time is 12ms whereas FMPID controller response have no overshoot and the settling time is 10ms.
Now the system is introduced to various ranges of network induced-delays varying from 0.5ms to 4ms. The result is shown in Figure 4.4 where it can be seen that as delay increases there is no overshoot but the settling time increases to 120ms.

Figure 4.5 shows the response of the system only when control signal is lost in the forward path for 3ms at 25ms. It is seen that the oscillation and the settling time increases to track the reference once again.

Similarly when feedback signal is lost in the feedback path for 2ms at 40ms, the response of the system is shown in Figure 4.6 where the oscillation increases and then it takes 9ms to settle at the desired output which is better than the PID controller performance.

Figure 4.7 shows the response of the networked DC motor control system when subjected to delay of 0.5ms in feed-forward path, 1ms in feedback path and loss of control signal in the feed-forward path for 2ms.

Figure 4.8 shows the response of the system when the networked DC motor control system is subjected to feed-forward delay of 0.5ms, feedback delay of 1ms and loss of feedback signal in feedback path for 2ms.

Figure 4.9 shows the response of the system when control signal in feed-forward path and feedback signals in feedback path are lost in the network.

When noise i.e. disturbance signal as shown in Figure 3.13 is introduced in the feed-forward path of the network the response of the system is shown in Figure 4.10.
Figure 4.3 Comparison of system responses using PID and FMPID controllers without delays and losses.
Figure 4.4  Output response of the system using FMPID Controller with varying delays in forward and feedback path
Figure 4.5 Comparison of system responses with PID and FM PID controllers when control signal is lost in feed-forward path.
Figure 4.6 Comparison of system responses with PID and FMPID controllers for loss of feedback signal in the feedback path.
Figure 4.7  Comparison of system responses with PID and FMPID controllers for loss of control signal and delays in network paths
Figure 4.8  Comparison of system responses with PID and FMPID controllers for loss of feedback signal and delays in network paths
Figure 4.9 Comparison of system responses with FMPID and PID controllers when feed-forward and feedback signals are lost.
Figure 4.10 Comparison of system responses with FMPID and PID controllers when noise is introduced in feed-forward path
From the simulation results it is found that the performance of FMPID controller is better than the PID controller with respect to overshoot and settling time when the delays, losses and disturbances occurs in the network path. Since the settling time of FMPID is larger, the fuzzy logic controller without PID controller is proposed in the next section for networked DC motor control.

4.4 NETWORKED DC MOTOR CONTROL USING FUZZY LOGIC CONTROLLER

In general, fuzzy logic controller is used for the control of a plant where the plant modeling is difficult. The fuzzy logic controller does not require plant models and measurement of network challenges. This is very important because the measurement of network delays and losses may be very difficult, if not impossible, because the challenges varies with many factors including number of stations, communication traffic of the network and implementation method of the network communication process. For such systems that are difficult to model, fuzzy logic controller has been successful by Mamdani.

The basic principle of fuzzy logic lies in the definition of a set where any element can belong to a set with a certain degree of membership. Using this idea, the knowledge of an expert can be expressed in a relatively simple form and the inference for given inputs can be implemented very efficiently. Due to these advantages, fuzzy logic controller is a very attractive method for NCS whose modeling is very difficult because of the stochastic and discrete nature of the network.
Figure 4.11 shows the block diagram of fuzzy logic controller for networked DC motor control where \( r(t) \) is the reference input, \( y(t) \) is the plant output, \( e(t) \) is the error signal between the reference input and plant output and \( u_f(t) \) is the control signal.

The trapezoidal fuzzy members are selected for membership functions. Three fuzzy linguistic variables, i.e., Small, Medium and Large are defined. In order to easily define the membership functions with different control specifications membership functions are expressed in relation with the maximum error that are widely used as design specifications. The coefficients are determined by several trial-and-error experiments with the plant without the network.

For execution of the fuzzy logic controller, the Mamdani’s min-max inference method and the central average defuzzifier are used. The rules are formulated considering the allowable error as follows:

- If \( e(t) \) is Small then \( u_f(t) \) is Small
- If \( e(t) \) is Medium then \( u_f(t) \) is Medium
- If \( e(t) \) is Large then \( u_f(t) \) is Large

The control signal \( u_f(t) \) produced by the fuzzy logic controller is sent to the plant through the network and the measurements of the output is also sent back to the controller via network where the network-induced delays and losses of signal may occur. The controller depending upon the input error signal to it, they produce the control signal to compensate the effects of the challenges.
4.5 SIMULATION RESULTS WITH FUZZY LOGIC CONTROLLER

In this section, the networked DC motor is controlled using Fuzzy Logic Controller as shown in the simulation model Figure 4.12. First the simulation is carried out by introducing delays in the feed-forward path and feedback path of the network. Then the system is subjected to delays in network path, loss of control signal in feed-forward path and loss of feedback signal in the feedback path and the results are studied. Finally the band-limited white noise is introduced in the feed-forward path and the performances of the fuzzy logic controller for networked DC motor control are studied by comparing the simulation results with PID controller and Fuzzy Modulated PID controller.
Figure 4.12 Simulation model of the system with FLC controller

Figure 4.13 shows the comparison of system performance using Fuzzy Logic Controller, Fuzzy Modulated PID controller and PID controller without delay and losses where

- PID controller response has 13.3% overshoot and 12ms as settling time.
- Fuzzy Modulated PID controller response has no overshoot compared to PID controller but settling time is 10ms.
- Fuzzy Logic Controller response has 3.3% overshoot and 6ms as settling time which is reduced than PID controller and FMPID controller.
Figure 4.13 Comparison of system responses using PID, FMPID and FLC without network-induced delays and losses
The Figure 4.14 shows the system performance using FLC when the system is introduced to various ranges of network induced-delays varying from 0.5ms to 4ms. The response of the system with FLC has 5.3% to 6.7% overshoot and around 8 to 16ms as settling time which is comparatively better than FMPID and PID controllers.

The simulation is carried out when the control signal is lost for 3ms in the feed-forward path as shown in Figure 4.15 and compared with FMPID and PID controllers. Figure 4.16 shows the system response when the feedback signal is lost for 2ms in the feedback path.

Then the simulation is carried out for the system when both delay and loss of signals occurs in the feed-forward and feedback path. Figure 4.17 shows the simulation result when the system is subjected to feed-forward delay of 0.5ms, feedback delay of 1ms and loss of control signal in the feed-forward path for 2ms.

Figure 4.18 shows the response of system when the loss of feedback signal for 2ms occurs with the feed-forward delay of 0.5ms and feedback delay of 1ms.

Figure 4.19 shows the response of the system when feed-forward and feedback signals are lost in the network path and compared with FMPID and PID controller.

When the band-limited white noise as shown in Figure 3.13 is introduced in the feed-forward path of the network, the response of the networked DC motor system with FLC, FMPID and PID controller are shown in Figure 4.20.
Figure 4.14 Output response of the system using FLC with varying delays in forward and feedback path
Figure 4.15  Comparison of system responses for loss of control signal in feed-forward path using FLC, PID and FMPID controllers
Figure 4.16 Comparison of system responses for loss of feedback signal in the feedback path using FLC, PID and FMPID controllers
Figure 4.17  Comparison of system responses for delays in network paths and loss of control signal using FLC, PID and FMPID controllers
Figure 4.18 Comparison of system responses for delays in network paths and loss of feedback signal using FLC, PID and FMPID controllers
Figure 4.19 Comparison of the response for system using FLC, FMPID and PID controller when feed-forward and feedback signals are lost
Figure 4.20  Comparison of the response for system using FLC, FMPID and PID controllers with noise introduced in feed-forward path.
The performance comparison of the FLC, FMPID and PID controllers for the networked control DC motor with network induced delays are tabulated in Table 4.1.

**Table 4.1  Comparison of performance of the networked DC motor control system using FLC, FMPID and PID Controller with network-induced delay (Set point = 150 rad/sec; Sampling Time = 0.5ms)**

<table>
<thead>
<tr>
<th>Time delay(ms)</th>
<th>Maximum overshoot (%)</th>
<th>Settling Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed-forward Path</td>
<td>Feed-back Path</td>
<td>P I D</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
<td>5.3</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>25</td>
</tr>
</tbody>
</table>

From the simulation results from Figures 4.13 to 4.20, it shows that when delay and losses occurs in the feed-forward and feedback paths, the tracking speed of the fuzzy logic controller system is faster than the FMPID and PID controllers with minimum distortion. Thus the result clearly shows the Fuzzy Logic Controller works better for the networked DC motor control with network challenges over Fuzzy Modulated PID controller and PID controllers. Therefore fuzzy logic control shall be an appropriate choice for NCS due to its robustness against uncertainties in the system parameters.
4.6 SUMMARY

This chapter has been focused on the application of fuzzy logic controller for NCS. The effectiveness of fuzzy logic control is verified on networked DC motor control using simulation. For comparative evaluation of the fuzzy logic control, PID and FMPID controllers are used for the motor control. From the simulation results it is clearly noted that the performance of the fuzzy logic controller does not deteriorate as much as that of the other controllers when the system is subjected to network-induced delays, disturbance through noise signals and losses of signals in the feed-forward and feedback network paths. This is because of the inherent robustness of the fuzzy logic controller against the parameter uncertainty. But still in order to improve the performance of the networked DC motor control with both delay and losses than the fuzzy logic controller, the artificial neural network and Neuro-Fuzzy controllers are introduced in the subsequent chapters.