Temperature and water level control in a multi-input, multi-output process using neuro-fuzzy controller

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Abstract. In this research, a simulation study for temperature and level control in a liquid (water) mixing process is proposed using MATLAB/Simulink. The objective of this control system is to maintain the temperature and water level at the set points in a liquid mixing process by controlling the flowrate of cold and hot water that enters the mixing tank. The mixing tank used in this study is assumed to have a volume of 80 liter, while the maximum flowrates of both water inputs are 15 liter/min, and the maximum temperature and level in the mixing tank are 90°C and 75 cm, respectively. The influence of one variable to the other is reduced using decoupling technique. In the development process of the controller, PI controller is used to generate the training data required by the ANFIS-based controller. The performance of the proposed controllers has been tested with several set points changes by observing its performances parameters, such as RMSE, rise time, settling time, and % overshoot as quantitative data. It also has been compared with a PI controller using the same set point changes as the ANFIS-based controller did. These results show that the ANFIS-based controller is generally better than the PI controller. It has the average RMSE values of 0.174 and 0.196 for temperature and level control respectively, while the PI controller has 0.21 and 0.20 average RMSE values for temperature and level control.

1. Introduction
The mixing process is one of the common processes that is often found in industrial process engineering. In general, the efficient mixing process could be a challenge, especially on an industrial scale. At present, the use of the mixing process is widely used in several different industrial areas. Control in the Multi-Input, Multi-Output (MIMO) process requires careful and meticulous design related to system irregularities, and process dynamics that unstable potentially. Various methods for designing process control are based on the use of linear and nonlinear control theories. There have been many development and implementation of various controller methods, one of which is a hybrid controller that combines two types of intelligent controllers such as neural networks and fuzzy logic.

Much research has been done regarding the MIMO process. One of them was research conducted by Muga [1]. He conducted research related to controlling temperature and liquid concentration in a simulation as well as real time implementation using PLC and MATLAB. The process of controlling these two variables is carried out using decoupling control to eliminate the influence between control variables. He controls the MIMO CSTR process using the PI Controller.

Machado [2] also conducted research on the same topic, the same controller (PI Controller), and used decoupling. The difference is that he implements it using Arduino Uno in his research. Thus, we hope that applying intelligent controls (Fuzzy Logic and Neural Network) in the control system can
produce ideal performance in this MIMO process. Given basically these two models can naturally adapt and cover each other’s shortcomings.

2. Method

2.1. Description of Process Simulation

The multivariable control process raised in this study is the process of mixing cold and hot water. This process has two variables controlled (level and temperature) of mixed water. The scenario created in this research is how this process can produce a product in the form of flow out water with a temperature value and level in a stable mixed tank when the process is running continuously. Both control variables obtained by controlling the flow in cold and hot water (liter/s). Thus, this process has two input variables \((w_h, w_c)\) and two control outputs \((h, T)\).

![Diagram of water mixing process and multi-loop control block](image)

Figure 1. (a) Water mixing process (b) Diagram block of multi-loop control

This process simulated continuously using Simulink MATLAB and takes place dynamically. This mixing process is quite difficult. Where these two variables affect each other. The flow in of hot water was enlarged to increase the temperature of the water in the mixed tank. When the hot water discharge was enlarged, the water level in the mixed tank will also go up. Likewise, the flow in of cold water was enlarged to increase the level of the water in the mixed tank. When this discharge was enlarged, the water temperature will decrease. From figure 1, we assumed that \(U_1(w_h)\) and \(U_2(w_c)\) inputs are flow in hot and cold water. \(Y_1\) output for temperature control and \(Y_2\) as level control output.

2.2. Mathematical Model of Process

Modeling is done by reviewing mass balance. It is assumed in this process that the liquid density is constant, no mass and heat is lost during the process, and the mixing process occurs perfectly. The main thing to consider in determining mass balance is consider to the volume controlled with the mass entering, and the mass going out.

\[
\begin{align*}
G_{p11} &= \frac{T'(s)}{W'h'(s)} = \frac{203.125}{(250s + 1)} \\
G_{p12} &= \frac{W'c'(s)}{H'(s)} = \frac{0.0079}{s} \\
G_{p21} &= \frac{W'h'(s)}{H'(s)} = \frac{0.0079}{s} \\
G_{p22} &= \frac{W'c'(s)}{s}
\end{align*}
\]
2.3. Control Valve Modelling

In this research, it is assumed that the control valve has a nonlinear flow so that a first order approach can be performed [3].

\[
\frac{M_s}{G_T} = \frac{K_v}{T_{cv} + 1}
\]

(3)

With \(K_v\) is the gain control valve and \(T_{cv}\) is time constant. The gain \(K_v\) is obtained using the relationship between the range of water discharge by entering the percent openings for control valve 1 with a value of 1.056 l/min as shown below:

\[
K_{v1} = \frac{\text{Output (Span of water discharge)}}{\text{Input (C}^\circ)} = 0.0176 \text{ C.liter/s}
\]

\[
K_{v2} = \frac{\text{Output (Span of water discharge)}}{\text{Input (meter)}} = 1.76 \text{ m.liter/s}
\]

(4)

(5)

Time constant \((T_{cv})\) is taken from experimental data with a value of 0.018 seconds. Then obtained the transfer function modeling for the control valve,

\[
\frac{M_s(s)}{G_c(s)} = \frac{0.0176}{0.018s + 1}
\]

\[
\frac{M_s(s)}{G_c(s)} = \frac{1.76}{0.018s + 1}
\]

(6)

2.4. Use of Decoupling Control

Decoupling is a technique that is useful for reducing the interaction between two (multivariable) loops in one process. One of its uses is when the set point changes for the first controller, then decoupling will make changes to this set point having no effect for the second controller. Some decoupling is based on a process model that is obtained under steady state conditions. \(G_{p11}, G_{p12}, G_{p21},\) and \(G_{p22}\) are the process transfer functions while \(G_c\) is the controller. \(T_{21}\) and \(T_{12}\) are decoupling functions obtained from the relationship between the process transfer functions. \(T_{21}\) is designed to reduce the effect of \(Y_{21}\) that arises from unwanted process interactions between \(U_1\) and \(Y_2\)

\[
T_{21} = -\frac{G_{p21}}{G_{p22}} = -1
\]

\[
T_{12} = -\frac{G_{p12}}{G_{p11}} = 1
\]

(7)

Figure 2. Simulation of process using PI controller

The simulation was done in Simulink by using the PI controller as the default system which useful as a producer of training data. The design of a multivariable controller system explained by figure 2.
2.5. Initiation of ANFIS Controller

ANFIS training on MIMO control systems requires training data from PI controllers as "teachers" for learning. In this study, ANFIS training for level control uses two input data (errors and error changes) and one output (MV) from the PI controller and 3 inputs (set points, errors, and error changes) for temperature control. Two inputs for this level control will be used each of the 5 gaussian type (MF) membership functions and will be trained for 10 epochs until the results of the RMSE training approach 0. The ANFIS training is also carried out for temperature control with the same type and number of MFs.

In the end, the results of ANFIS training will follow exactly like the PI controller. Thus, after doing the training, we did the optimization to get the ANFIS controller performance better than PI. The ANFIS training results for the two controls are then exported into a .fis file to be implemented in the process simulation in MATLAB Simulink.

![Figure 3. Simulation of process using ANFIS controller](image)

3. Results and Discussion

System testing is done in two ways, namely providing changes in set point temperature, level and providing interference input to see the performance of the PI and ANFIS controllers. Changes in this set point will affect changes in valve openings for hot and cold-water flow where the temperature (°C) and level (meter) inputs have been scaled to synchronize the dimensions between system input and output. So, the system consistently works in the same dimensions or it can be said that the input control valve transfer function is in the form of current (mA).

3.1. Testing Process with Set Point Changes

Determining PI constants in process control is done autotune by considering robust and still in the range of hot and cold-water discharge. The largest discharge that can be used is 0.25 l/s. As such, we look for PI constants that can produce MV (discharge) outputs that do not exceed 0.25 l/s. PI constant is determined by considering MV (discharge) will produce a slow process with rise time in the range of 500 seconds. Thus, obtained PI constants for temperature and level control as shown in table 1.

| Table 1. Constant of PI controller |
|-----------------------------------|
| Temperature                      | P  | I   |
|        0.124                      |    | 0.0005 |
| Level                           | 0.151 | 1.124 |

ANFIS training results from PI data will produce performance like PI controllers. We do the optimization by changing the MF range of each training input. So, we get a better process graph from the PI controller. Both controller testing for mixed temperature control is carried out with set point changes of 35°C, 70 °C and 50 °C as shown in figure 4 (a).
Figure 4. Temperature (a) and level (b) control with set point changes

Table 2. Performance of PI and ANFIS controller for temperature control

| Set Point | RMSE     | Overshoot (%) | Rise Time (s) | Settling Time (s) |
|-----------|----------|---------------|---------------|-------------------|
|           | PI       | ANFIS         | PI            | ANFIS             | PI            | ANFIS         |
| (0-35) °C | 0.2113   | 0.1136        | 0.028         | 0.085             | 549.78        | 231.8         | 912.12        | 548.48         |
| (35-70) °C| 0.2113   | 0.2040        | 0.014         | 0               | 550.78        | 509.09        | 778.78        | 846.96         |
| (70-50) °C| 0.2113   | 0.2052        | 0.002         | 0               | 551.78        | 527.29        | 740.3         | 900            |

Table 3. Performance of PI controller for level control

| Set Point | RMSE   | Overshoot (%) | Rise Time (s) | Settling Time (s) |
|-----------|--------|---------------|---------------|-------------------|
|           | PI     | ANFIS         | PI            | ANFIS             | PI            | ANFIS         |
| (0 – 0.35) m | 0.1974 | 0.1983        | 0.084         | 0                | 522.33        | 522.25        | 815.20        | 915.2          |
| (0.35 – 0.6) m | 0.1914 | 0.1995        | 0.065         | 0                | 462.16        | 516.23        | 694.25        | 919.25         |
| (0.6 – 0.4) m | 0.2128 | 0.1929        | 0             | 0               | 583.17        | 505.04        | 1531          | 905.06         |

3.2. Performance Analysis

The performance of a controller can be seen from several things such as the speed of response, and the ability of a controller to maintain stable conditions. The system in the form of an open loop shows a graph of a linear level control process, and a nonlinear temperature control process does not reach the set point. Thus, the use of a controller is indeed needed to overcome the overloading of tank levels that keeps increasing beyond the set point. The choice of PI constants also considers robust or graphical
form of the process which tends to be sloping and has no overshoot even though it has a slow process response. That is because, if the level control chart has overshoot, there is a possibility that the tank level will spill when given a maximum set point at 0.75 meters.

Testing the change in set points on the PI and ANFIS controllers is characterized by the parameters above. The RMSE value is obtained with normalized process data for one set point change. In the temperature control when changing the first set point (0-35°C), the process data will show a large error during the first second with a span of 1 and 0. 35 °C means 1 and 0 °C means 0. Finally, for the same range span such as from 35 °C to 70 °C also shows a same RMSE value.

%Overshoot is seen from the first peak of the process response to the process settling time. The % OS difference between set point changes from 0-35 °C for PI and ANFIS controllers shows that PI controllers have smaller OS%. This happens because we focus more on the small RMSE value on the ANFIS controller. However, for changing the set point 35-70 °C shows that ANFIS controllers can make the process not have% OS and have a small RMSE value at the same time.

Rise time is seen from the time when the process is between 10% and 90% of the steady state. Rise time on the ANFIS controller when the set point is going to 35 °C is very fast at 231.8 seconds. But afterwards, ANFIS showed a constant rise in rise time of 509 seconds for an increase in SP of 35-70 °C and 530 seconds for a decrease in SP of 70-50 °C. Overall, the rise time of ANFIS controllers shows a faster response than PI controllers for the same SP changes.

From tables 2 and 3, information is obtained about the process on the ANFIS controller which does not have overshoot. This was done to avoid having excess tank levels. The goal in ANFIS controllers at the controller level is to get a very small RMSE. This is done because in the PI controller, the steady state process does not reach the set point. The Underdeveloped PI control process is around 0.084% above the set point. Though the response process has been sought the best when doing autotune. Then, this problem can be solved by ANFIS controllers which have stable conditions adjusting set points.

4. Conclusion
From this study, it can be concluded that simulation of the MIMO (Multiple-Input, Multiple-Output) process in this study is carried out by using a decoupling control to reduce the effect of the first controller on the output level (H'(s)), and the effect of the two controllers on the output temperature (T'(s)). The decoupling function gain for both controls is obtained with the values $T_{21} = -1$ and $T_{12} = 1$. The performance of the ANFIS controller is better at handling slow process responses and there is no overshoot when tested with a change in set point which is the cause of the smaller RMSE value than the PI controller.

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