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Design of 3×3 Multi Input Multi Output (MIMO) Decoupling on Coupled Tank System with PID Controller

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Abstract: Multivariable processes are the general classification for process features in the chemical industry. The variables in a single process unit interact with one another through more than one input and output. Since parameters interact with one another, changing one parameter's variable requires changing another parameter's variable as well. Further research is needed to determine how to create controllers that can handle interactions in the process. A MIMO control system is exemplified by the coupled tank system. Coupled tanks are present, and they communicate with one another by horizontal pipes. An interacting system can be represented using a coupled tank setup. Decoupling can be added to reduce the interactions that take place between variables. According to the results of the simulation, adding decoupling reduces the IAE value compared to not adding it. When the setpoint for tank level 1 (H1) was changed, the system's IAE value was 17.35 without the addition of decoupling, whereas it was 11.71 with it.

Keywords: Coupled tank system; Decoupling; Interaction; MIMO 3×3; Multivariable

Introduction

Chemical industry process features are typically characterized as multivariable processes. The variables in a process unit interact with one another in more ways than one since there are several inputs and outputs in a single process unit. In every circumstance during the process, an automatic control system is required. The parameters include the following: temperature, level, pressure, flow rate, and composition. The variables in these conditions interact with one another, allowing the variables in other parameters to be changed in order to alter the variables in one parameter. Further investigation is necessary to create controllers that can handle interactions in the process (Morari & Zafiriou, 1982).

In the process sector, there are various types of tanks, including coupled tanks and solitary tanks, both of which are separate from other tanks and do not have a connection (Sadli, 2014). Coupled tanks are categorized as MIMO (multiple input, multiple output) systems, where MIMO system settings are more challenging than SISO (single input, single output) systems (Ogata & Brewer, 2010; Sousa et al., 2020). A nonlinear coupled tank is one that has two tanks connected by a pipe, such as the coupled tank system (Pangestu et al., 2022; Saputra et al., 2018; Ulum, 2017). Despite having a straightforward design, the coupled tank system can reflect interactions in processes and a model of a three-by-three interconnected system.

An engineer finds it challenging to build controllers for MIMO systems because of interactions. To avoid interactions across loops, a variety of techniques have been developed, including relay autotuning, optimization, and detuning techniques. This control technique has the benefit of being simple to use and comprehend (Azizah, 2018; Fellani & Gabaj, 2015). However, if the interaction is too strong, it does not offer good performance (Q. B. Jin & Liu, 2014). Decoupling is a powerful control for dealing with interaction issues. A multivariable process is divided into a number of independent single loop sub-systems by the decoupler (Vijula & Devarajan, 2014).

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According to earlier studies, the decoupling strategy is only relevant for two-input, two-output (TITO) systems. The One Degree of Freedom Internal Model Control (1DoF IMC) controller was used in prior research to implement inverse decoupling on a 2×2 MIMO system. The IAE value is less than without inverse decoupling as a result of the addition of inverse decoupling (Azizah et al., 2020). Then, 2DoF IMC was used as the controller to continue the investigation(Q. Jin et al., 2016). The outcomes show that inverse decoupling can greatly minimize interaction (Juwari Purwo Sutikno et al., 2019; Üstüner & Taşkin, 2019). Decoupling for 3×3 MIMO systems hasn't received much attention, though. This is due to the fact that the decoupling calculations become more challenging the higher the system size (Azizah, 2022).

The decoupler is made up of two matrices, the Dd matrix and the Do matrix, which act as a direct conduit and a feedback loop, respectively, between the process input (u) and the controller output (c), respectively. Due to the fact that each process input has only a direct link, the Dd matrix has n elements and is non-zero. However, the Do matrix does not require this relationship. This is due to the fact that Do's flow direction is the polar opposite of Dd's. The transposition of the non-zero element of Dd is the Do element, which must be equal to zero (Garrido et al., 2014; Huang & Lin, 2006).

The decoupling approach is a technique for removing the effect of interaction between a MIMO system's inputs and outputs, making the system appear to operate like a SISO system (Bharathi & Selvakumar, 2012). Decoupling can reduce process interference. The plant stabilizes when one of the inputs is changed (Puspitarini et al., 2017).

The transfer function value for the MIMO 3×3 System 2 Tanks is entered to derive the decoupling equation. The 33 MIMO system's decoupling matrix's shape:

$$D = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix} \quad (1)$$

The ideal decoupling process (Vijula & Devarajan, 2014) states that the decoupling diagonal element $D_{11}=D_{22}=D_{33}=1$, resulting in the decoupling matrix as follows:

$$D = \begin{bmatrix} 1 & D_{12} & D_{13} \\ D_{21} & 1 & D_{23} \\ D_{31} & D_{32} & 1 \end{bmatrix} \quad (2)$$

The decoupling matrix is multiplied by the tank system transfer function:

$$G \times D = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} \begin{bmatrix} 1 & D_{12} & D_{13} \\ D_{21} & 1 & D_{23} \\ D_{31} & D_{32} & 1 \end{bmatrix} \quad (3)$$

The diagonal elements of the G-D matrix are 0 for optimal decoupling, hence the matrix's product is

$$G \times D = \begin{bmatrix} G_{11} + G_{12}D_{21} + G_{13}D_{31} & G_{11}D_{12} + G_{12} + G_{13}D_{32} & G_{11}D_{13} + G_{12}D_{23} + G_{13} \\ G_{21} + G_{22}D_{21} + G_{23}D_{31} & G_{21}D_{12} + G_{22} + G_{23}D_{32} & G_{21}D_{13} + G_{22}D_{23} + G_{23} \\ G_{31} + G_{32}D_{21} + G_{33}D_{31} & G_{31}D_{12} + G_{32} + G_{33}D_{32} & G_{31}D_{13} + G_{32}D_{23} + G_{33} \end{bmatrix} \quad (4)$$

Based on equation (4) above, substitution is then carried out to obtain equations D_{12}, D_{13}, D_{21}, D_{23}, D_{31}, and D_{32}:

$$D_{12} = \frac{G_{13}G_{32} - G_{12}G_{33}}{G_{11}G_{33} - G_{31}G_{13}} \quad (5)$$

$$D_{13} = \frac{G_{23}G_{12} - G_{22}G_{13}}{G_{22}G_{11} - G_{21}G_{12}} \quad (6)$$

$$D_{21} = \frac{G_{31}G_{23} - G_{21}G_{33}}{G_{33}G_{22} - G_{23}G_{32}} \quad (7)$$

$$D_{32} = \frac{G_{31}G_{12} - G_{32}G_{11}}{G_{11}G_{33} - G_{31}G_{13}} \quad (8)$$

$$D_{23} = \frac{G_{21}G_{13} - G_{23}G_{11}}{G_{22}G_{11} - G_{21}G_{12}} \quad (9)$$

$$D_{31} = \frac{G_{32}G_{21} - G_{31}G_{22}}{G_{33}G_{22} - G_{23}G_{32}} \quad (10)$$

Method

The following are the steps taken in the research process to address the issue at hand:

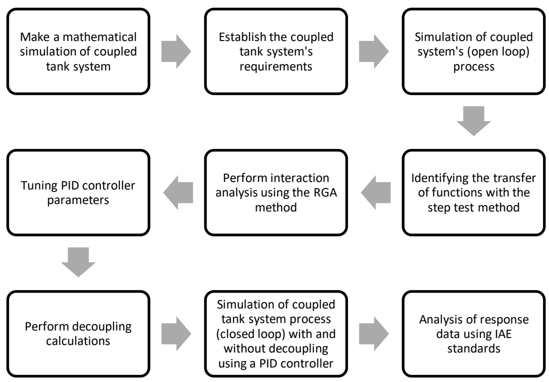

Figure 1. Research flow diagram

The equation for coupled tanks in the system is nonlinear and was obtained using the mass balance and the Bernoulli equation for each tank. It is as follows:

$$A_i \frac{dh_i}{dt} = k_i u_i - a_i\sqrt{2gh_i} \quad (11)$$

The tank outlet diameter, tank height, and tank diameter are all defined in terms of size. Determine the desired water temperature in tank 1 and the desired water level in each tank after that. The flow rate to tanks 1 and 2, designated as U_1 and U_2, is then calculated, and the heat provided is based on the mass balance and energy balance at steady state circumstances (Sim et al., 2017; Subiantoro, 2010). The model requirements for a coupled tank system are shown in Table 1.

Table 1. Coupled Tank System Model Specifications

Specifications	Value
Tank Height (1 and 2)	0.5 m
Base diameter (1 and 2)	0.2 m
Tank Bottom Pipe Diameter (1 and 2)	0.00925 m
Tank Horizontal Pipe Diameter (1 and 2)	0.00683 m

Without employing a controller, coupled tank system process simulation was performed. The objective is to get the system to its steady state condition.

When the system is open loop, which means that no controller has yet been added to it, the transfer function is identified using the step test approach. Once the process has stabilized, a 3-5% step change is implemented. By adopting a strategy that reflects the nature of the process that occurs, the process curve can be found.

Based on the steady state gain data, the transfer function calculated using the step test method then assesses the interaction with the RGA approach. The end result is a suggested pairing setup for a 3×3 MIMO system. The Ziegler-Nichols methods are used to calculate the tuning of the controller parameters (Darajat & Istiqphara, 2021). Decoupling calculations using equations (5) through (10) to decoupling calculations based on the step test method's transfer function.

Closed loop simulations are then performed using the calculated control and decoupling parameters. To determine whether the controller can track the setpoint, the simulation is run while altering the setpoint. Comparisons between simulation results with and without decoupling are made for coupled tank system process utilizing a PID controller. The IAE (integral absolute error) criteria are used to compare closed loop response graphs.

Result and Discussion

Openloop Simulation of Coupled Tank System

The interactions that take place during the process were investigated using a simulation of a two-tank system. The coupled tank system has a straightforward architecture but can represent a 3×3 MIMO model and process interaction. To make the simulation process easier, the tool specs and stable conditions are established from the beginning. The coupled tank system consists of two identically sized tanks that are joined by a pipe on the side. The bottom of each tank has an exit hole. The tank is 0.5 meters in height and 0.2 meters in base diameter. Water is the substance that is used. To start, the water levels in tanks 1 and 2 are 0.3 and 0.4 meters, respectively.

Figure 2 illustrates the coupled tank system's layout. Water is supplied by flows 1 and 2 at a flow rate of U_1 to tank 1 and U_2 to tank 2, respectively, with a ratio of 0.8. The water flows via flow 3 from tank 2 to tank 1 because tank 1 has a lower water level than tank 2. It comes with a Q_1 heater in tank 1. The two-tank system has three regulated variables, H_1, H_2, and T_1, as well as three manipulated variables, U_1, U_2, and Q_1. The system creates a Multi-Input-Multi-Output (MIMO) 3×3 network from these variables (Prajapati & Roy, 2016).

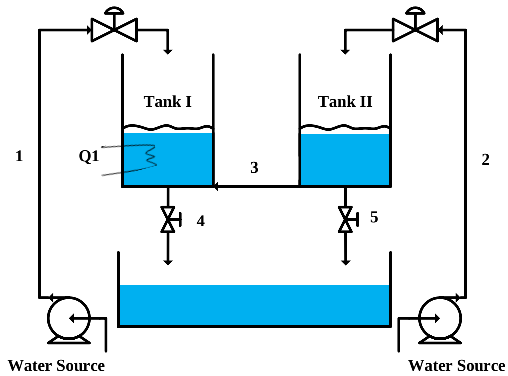

Figure 2. Coupled tank system scheme

Based on the scheme in Figure 1, the mass balance and energy balance equations for coupled tank system are as follows (Echsony et al., 2018; Mahapatro, 2018; Muntaser & Buaossa, 2017; Sim et al., 2017).

Mass Balance Tank 1:

$$A_1 \frac{dh_1}{dt} = \gamma_1 k_1 u_1 + a'_2\sqrt{2g(h_2 - h_1)} - a_1\sqrt{2gh_1} \quad (12)$$

Mass Balance Tank 2:

$$A_2 \frac{dh_2}{dt} = \gamma_2 k_2 u_2 - a'_2\sqrt{2g(h_2 - h_1)} - a_2\sqrt{2gh_2} \quad (13)$$

Energy Balance Tank 1:

$$A_1\rho C \frac{d\, h_1.T_4}{dt} = W_1\rho C(T_1 - T_{ref}) + W_3\rho C(T_3 - T_{ref}) + Q_1 - W_4\rho C(T_4 - T_{ref}) \quad (14)$$

Next, using the First Order Plus Death Time (FOPDT) method (Seborg et al., 2011), transfer function identification seeks to ascertain the transfer function of the coupled tank system (Rahmat & Md Rozali, 2012). Each manipulated variable, namely U_1, U_2, and Q_1, received a step change of 10% at this point. The response of the controlled variables, H_1, H_2, and T_1, is then observed. The result of the transfer function is as follows

$$G_p = \begin{bmatrix} Gp_{11} = \frac{42.8212e^{-0,73s}}{95.73s+1} & Gp_{12} = \frac{22.403e^{-4,73s}}{181.73s+1} & Gp_{31} = 0 \\ Gp_{21} = \frac{22.8281e^{-6,73s}}{173.73s+1} & Gp_{22} = \frac{47.449e^{-0,09s}}{104.73s+1} & Gp_{32} = 0 \\ Gp_{31} = \frac{-268.57e^{-0,09s}}{263.73s+1} & Gp_{32} = \frac{-139.149e^{-0,09s}}{261.73s+1} & Gp_{33} = \frac{-0.3229e^{-0,09s}}{57.73s+1} \end{bmatrix} \quad (15)$$

It is crucial to do interaction analysis in the MIMO system to determine the ideal pairing between the controlled and manipulated variables. The Relative Gain

Array (RGA) results are based on the Gain (K) value for each 3×3 MIMO transfer function.

$$\lambda = \begin{bmatrix} 1.3364 & -0.3364 & 0 \\ -0.3364 & 1.3364 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (16)$$

Based on the results in equation (2), the diagonal matrix is positive and ≥ 1, so the correct pairing recommendation is 1-1/2-2/3-3. This means that the correct pairs are H_1-U_1, H_2-U_2, and T_1-Q_1. The H_1 level is controlled by manipulating the flow rate of U_1, the H_2 level is controlled by manipulating the flow rate of U_2, and the temperature of T_1 is controlled by manipulating Q_1.

Closedloop Simulation of Coupled Tank System

Closedloop simulation requires a controller on a 3x3 MIMO model system circuit. The controller used in this research is Proportional Integral Derivative (PID) with the Ziegler-Nichols method (Ranjan et al., 2015). Table 2 is the result of tuning the controller parameters in each pairing. There are three parameters used, namely Kc, τ_I, and τ_D.

Tabel 2. PID Parameters

Pairing Controller	K_c	τI	τD
H_1-U_1	2.89	1.99	1.05
H_2-U_2	23.09	128.3	1.04
T_1-Q_1	-1871.42	-10398.05	-84.2

Based on the transfer function in equation (15), then the decoupling calculation is performed using the Matlab software with the results in equation (17) to equation (20). The role of decoupling in the process is to be able to break down processes that have multivariable properties into separate single loop subsystems. D23 and D13 are zero because the decoupling product results in a static gain.

$$D_{12} = \frac{-3.998e04s^2 - 1110s - 7.234}{1.451e05s^2 + 3311s + 13.83} \quad ; e_{12} = -0.0183 \quad (17)$$

$$D_{21} = \frac{-4.457e04s^2 - 1198s - 7.371}{1.537e05s^2 + 3546s + 15.32} \quad ; e_{21} = -0.0013 \quad (18)$$

$$D_{32} = \frac{-7.451e11s^4 - 2.347e10s^3 - 2.118e08s^2 - 4.946e05s + 58.13}{1.66e10s^4 + 3.912e08s^3 + 3.211e06s^2 + 1.11e04s + 13.83}$$
$$e_{32} = -0.8972 \quad (19)$$

$$D_{31} = \frac{-2.973e12s^4 - 1.064e11s^3 - 1.261e09s^2 - 5.933e06s - 9567}{1.924e10s^4 + 4.41e08s^3 + 3.578e06s^2 + 1.232e04s + 15.32}$$
$$e_{31} = -0.9127 \quad (20)$$

The software Matlab Simulink is used to conduct closed-loop simulation. There are two simulations, one of which is a closedloop MIMO 3×3 simulation without decoupling and the other of which is a closedloop MIMO 3×3 simulation with decoupling in Figure 3. Internal Absolute Error (IAE) comparisons between the outcomes of the two simulations were made in order to identify the best outcome.

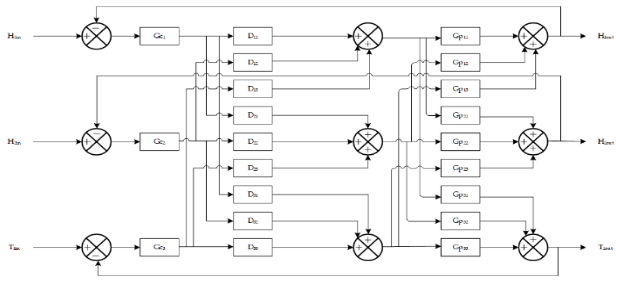

Figure 3. Closedloop MIMO 3×3 simulation with decoupling

In the closed loop simulation, Level H_1 was given a setpoint change in Figure 4 at the 500^{th} second from 0.3 to 0.4 m. Changing the setpoint on H_1 causes H_2 to change in Figure 5. However, this does not apply to the T_1 variable. Changes in level on H1 do not affect T_1, so T_1 remains at its setpoint (Figure 6).

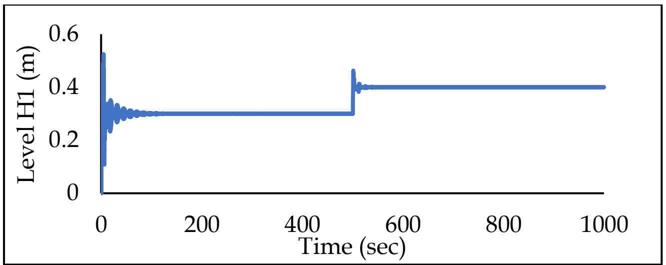

Figure 4. PID controller simulation results without the addition of decoupling at level H_1

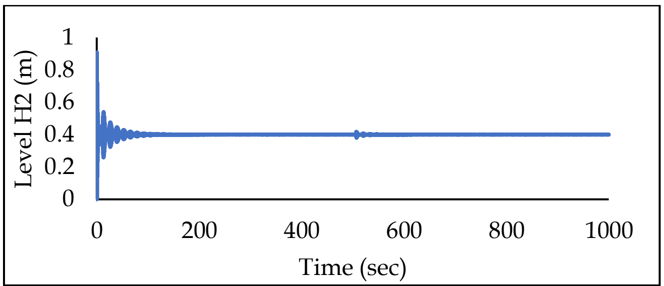

Figure 5. PID controller simulation results without the addition of decoupling at level H_2

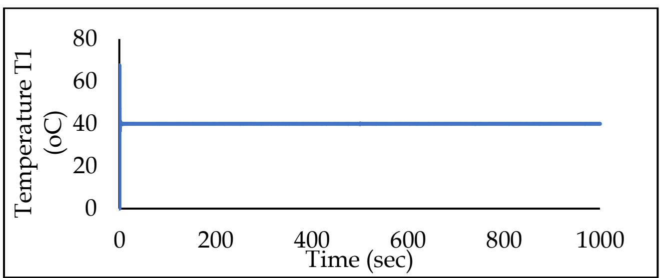

Figure 6. PID controller simulation results without the addition of decoupling at temperature T_1

The same thing is done in the coupled tank system simulation with the addition of decoupling. Overall, the response results (Figure 7 to Figure 9) obtained are almost the same as the simulation without decoupling. However, quantitatively, when viewed from the IAE values obtained in Table 3, the simulation with the addition of decoupling produces a smaller IAE value compared to the simulation without decoupling. This proves that a change in the H_1 variable does not significantly change the other variables because the interaction between the variables has been minimized by the addition of decoupling.

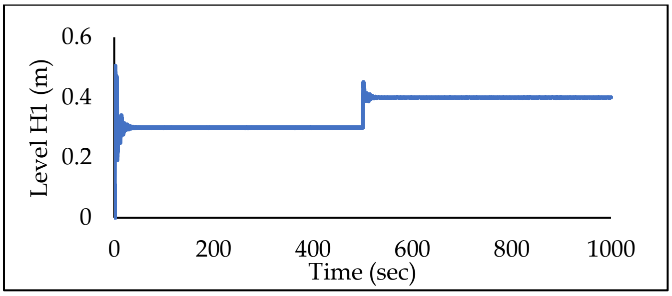

Figure 7. PID controller simulation results with the addition of decoupling at temperature H_1

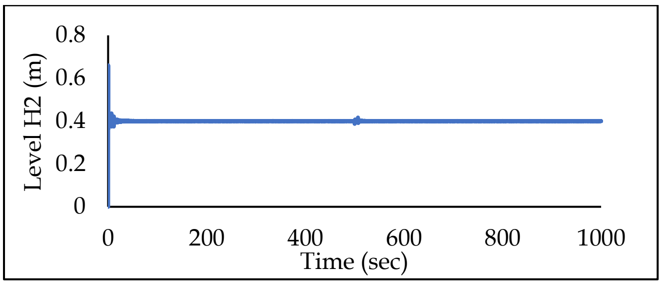

Figure 8. PID controller simulation results with the addition of decoupling at temperature H_2

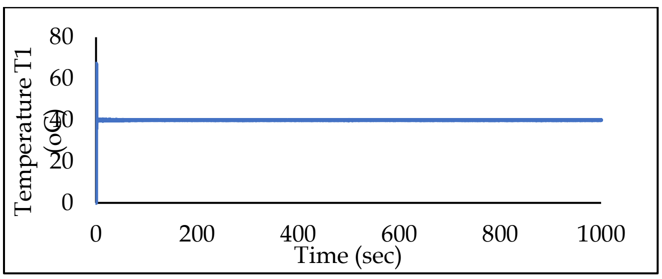

Figure 9. PID controller simulation results with the addition of decoupling at temperature T_1

Table 3. Comparison of IAE Value

Setpoint change	IAE MIMO 3×3 Value Without Decoupling	IAE MIMO 3×3 Value With Decoupling
H_1	17.35	11.71
H_2	1.87	0.34
T_1	1.73	1.79

Conclusion

Based on the simulation results, the output response to the controller scheme with decoupling produces a smaller IAE value compared to the controller scheme without decoupling. This proves that changes in one variable do not change much in other variables because the interaction between variables has been minimized by decoupling.

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Author Contributions

Conceptualization, Z. A.; methodology, Z. A.; software, Z. A.; writing—original draft preparation, Z. A.; formal analysis, Z.A.; investigation, Z. A.; visualization, Z. A.; writing—review and editing, L. F.; validation, L. F.; supervision, L.F.; resources, L. F.

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Conflicts of Interest

The authors declare no conflict of interest

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