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RESEARCH

PID control implementation in multiple input and multiple output (MIMO) water mixing tank via Ziegler–Nichols and direct synthesis methods

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This study deals with the modeling of two PI controllers to control first-order systems [cold water (CW) to tank level and hot water (HW) to temperature] using Ziegler–Nichols (ZN) and direct synthesis methods and to test both controllers for set-point tracking and disturbance rejection modes for multiple input and multiple output (MIMO) water mixing tank. The ZN method is a technique used for tuning controllers, and it used both proportional and integral actions in the present investigation. This method was performed by setting the integral (I) and derivative (D) gains to zero. It was applied to the open-loop reaction of the process to the change in the water level and the temperature (the control variables) and the plotter on the computer recorded the response. The evaluated process variables, such as K (for the proportional action) and ? (for the integral action), are plugged into the ZN equation with the specific multiplier constants for the gains of a controller with PI actions. The ZN technique was utilized to obtain a PI controller for both the CW to tank level system and the HW to temperature system. The direct synthesis (DS) method was applied to a desired closed-loop transfer function. The design of the controller was based on a process model. This method was applied to set-point changes in the control system and later fixed to responses to disturbances. The DS technique was implemented on the two systems, the CW to tank level and the HW to temperature. It was able to control the impact of the sensitive HW to temperature system. However, the controller performance across the CW to tank level system was extremely inefficient as oscillations were observed.

Keywords: Ziegler–Nichols method, direct synthesis method, multiple input and multiple output (MIMO) water mixing tank, process and controlled variables

Introduction

The objectives of the study were to model two PI controllers to control first-order systems (CW to tank level and HW to temperature) using Ziegler–Nichols (ZN) and direct synthesis (DS) methods and to test both controllers for setpoint tracking and disturbance rejection modes. The setpoint represented either the level (controlled by CW) or the temperature (controlled by HW), and the disturbance rejection represented how well the model rejected the unused stream, which was either cold water or hot water according to which control variable was targeted. Ziegler–Nichols is a popular technique used for tuning controllers, and in this investigation, it used both proportional and integral actions. It tested the open-loop reaction of the process to the change in the water level and the temperature (the control variables), and the response was recorded by the plotter on the computer. The calculated process variables, which are K (for the proportional action) and T (for the integral action), are plugged into the ZN equation with the specific multiplier constants for the gains of a controller with PI actions. In the direct synthesis (DS) method, the controller is designed based on the process model and the desired closed-loop transfer function. Industrially, the advantage of using the DS method is that the desired output behavior of the closed loop is easily specified as a trajectory model according to the targeted process design (1–3).

Materials and methods

The experimental setup was already set for the testing of the parameters of the controllers that were calculated. A step change to the level set-point was added, and the gain was increased until there was sustained oscillation. At this condition, the ultimate gain and the period of oscillation were obtained. Similarly, a step change to change the temperature set-point was also carried out to obtain the same parameters as before. These parameters for each set-point change were used to calculate the controllers' parameters to be tested. These parameters were the controller's gain (proportionality constant) and the integrators' time constant in the design of the PI controller. These calculations were done using the DS method and the ZN method. The obtained PI controller parameters were tested on the experimental setup for each method of calculation. The designed controllers' parameters were tested by inputting them into the controlling system the setup. A change in the water level set-point was done, and the level was allowed to be steady. The waiting time was about 10 min. Similarly, a change in the temperature set-point was carried out with a waiting time of about 10 min to allow for a steady state. The change in the response of the tank water level and the temperature changes were observed from the response graph. The performances of the designed controller by the methods were compared based on the output on the monitor. The designed controllers were different in the dead time of response. This was indicative of a difference in performance. The applicability of each method and the PI controller, in general, was also inferred from the response of the experimental setup (4, 5). The Labview software was used to collect the data from experiments and is a data acquisition software for this experimental setup (3, 4).

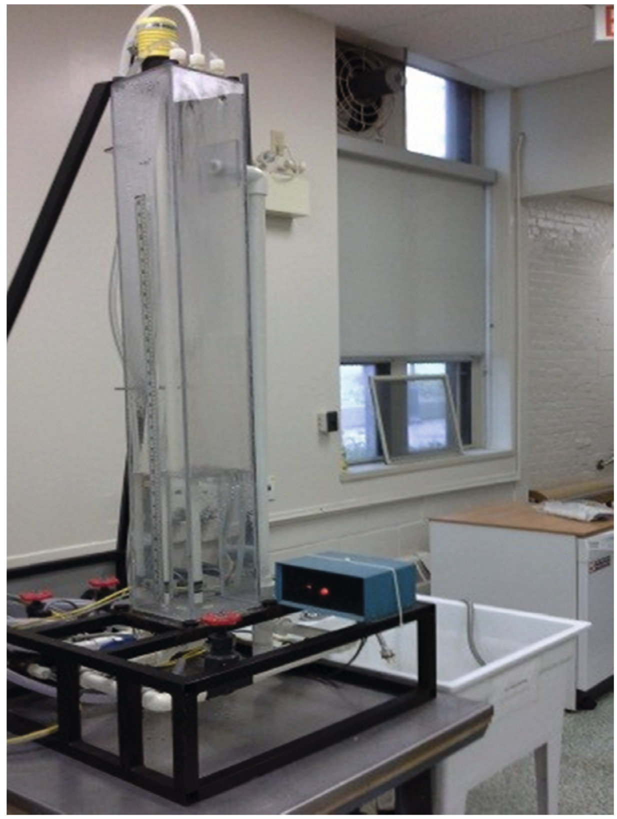

FIGURE 1 | Multiple input and multiple output (MIMO) apparatus.

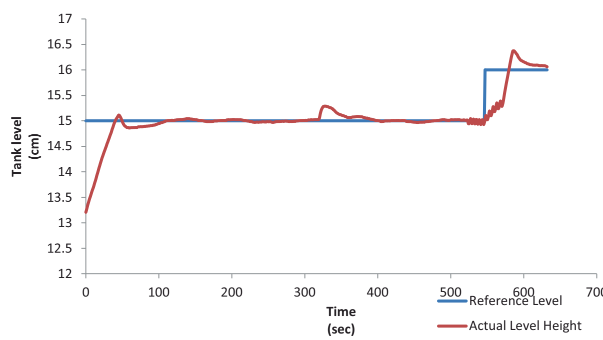

FIGURE 2 | Cold water (CW) to tank level—ZN technique.

Experimental setup

As seen in **Figure 1**, the laboratory experiment consisted of a multiple input and multiple output (MIMO) mixing tank apparatus, to study key system characteristics such as outlet flow, gain, delay, and time constants. These characteristics were found by controlling the opening and closing of the cold and hot water valves and observing the system stabilize at a certain value of Uc and Uh. The step change was used to study how the control variable is affected by changes in the manipulated variables. The control variable was carefully observed after a step change was made in any of the manipulated variables. Depending on the response of the control variable, the system was classified as a proportional control system, an integral control system, a control system with dead time, or a control system with energy-storing components. Some systems can reach a new equilibrium point and are said to be self-regulating. Systems that are not able to reach a new equilibrium point are therefore non-self-regulating. The latter are usually designed with closed-loop control.

Sometimes, the control variable does not respond to the changes in the manipulated variable immediately. This is known as delay and can be caused by dead time, lag, or storing components. Dead time is the difference in time when a change is initiated in the manipulated variable and when the control variable responds to that change. Systems that have dead times tend to oscillate. Delay due to lag occurs when a bulk material fed to a system at a certain end is only noticed at the output terming after a certain amount of time

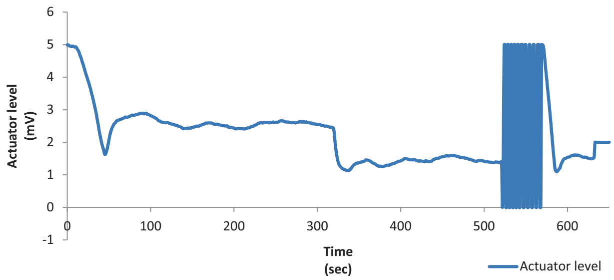

FIGURE 3 | Actuator of CW to tank level vs. time—ZN.

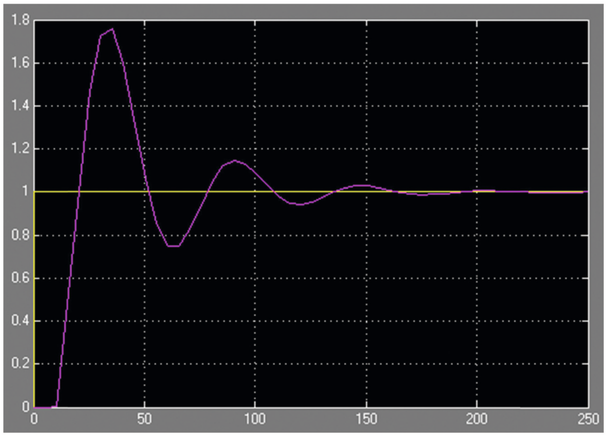

FIGURE 4 | Theoretical data of the tank level vs. time—ZN.

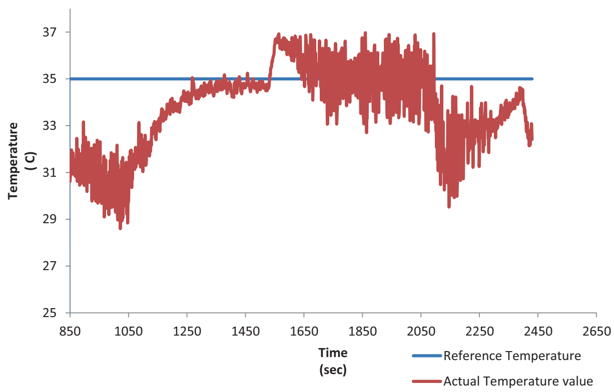

FIGURE 5 | Hot water (HW) to temperature—ZN technique.

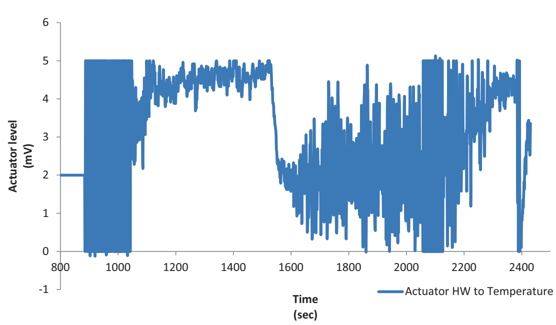

FIGURE 6 | Actuator level of HW to temperature—ZN.

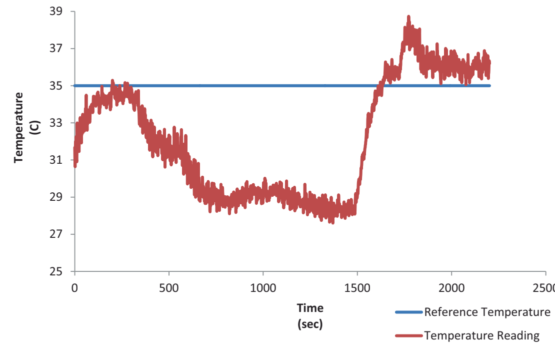

FIGURE 7 | Hot water (HW) to temperature—DS.

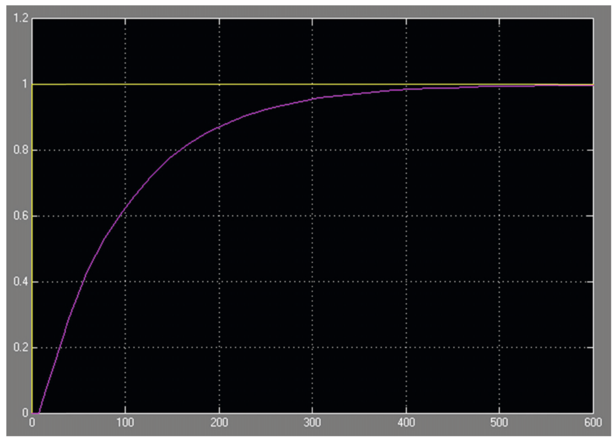

FIGURE 8 | Theoretical HW to temperature—DS technique.

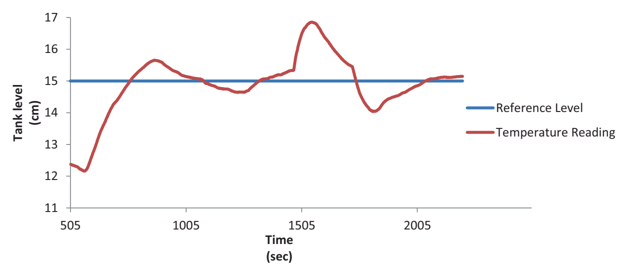

FIGURE 9 | Cold water (CW) to tank level system—DS.

has elapsed. Delays are also caused by some components of the system that can store energy. Gain, on the other hand, is a proportional value that shows the relationship between the magnitudes of an input to the output at a steady state. Gain can be altered; however, this should be done within a safe zone to avoid the system to become unstable. An increase in gain generally leads to a decrease in rising time. The time constant is the parameter that characterizes the step input of a first-order linear time-invariant system. A time constant can be used for the analysis of thermal systems where there is either heating or cooling of the system (6).

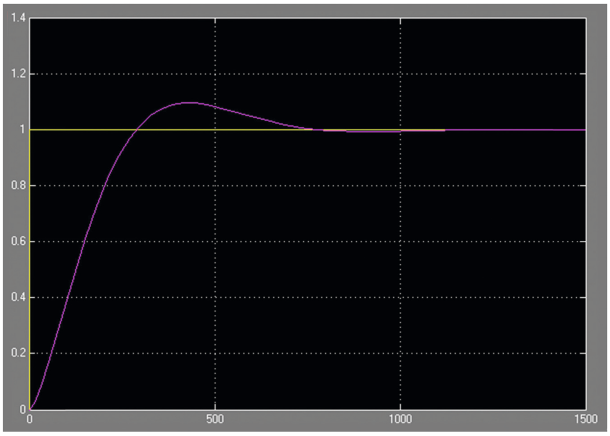

FIGURE 10 | Theoretical CW to tank level—DS.

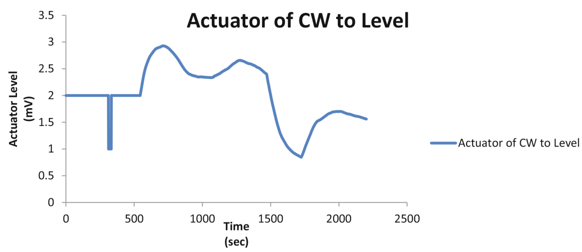

FIGURE 11 | Actuator of CW to tank level—DS.

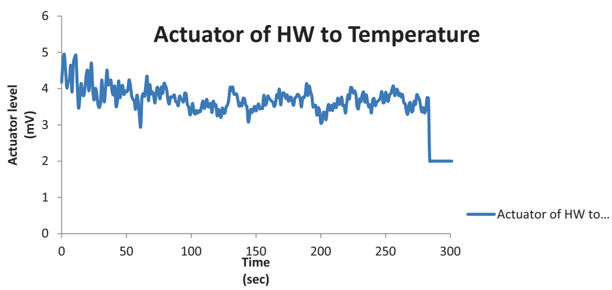

FIGURE 12 | Actuator of HW to temperature—DS.

Results and discussion

The experiment dealt with PID control implementations. Two multiple methods were utilized to obtain the magnitudes of the PI controller. The two methods were the ZN design method and the DS method. Each method had its advantages and disadvantages in terms of its applicability and the response it generated. Furthermore, a comparison was done between the theoretical plots and the experimental plots; the respective futures of each theoretical plot were examined to predict the overall performance of the controller (2).

Figure 2 demonstrates the experimental results obtained for the CW to tank level data. The design technique that was utilized to generate the data was the ZN design technique. A PI controller was implemented to diminish the steady-state offset between the reference level and the actual level. The two parameters obtained, using the ZN technique for the PI controller, were 3.742 and 33 for both the proportional action and the integral action, respectively. As seen in Figure 2, a relatively small overshoot was observed. Furthermore, the controller responded very well to input disturbances, as observed at 350 s. Finally, the controller adjusted quickly to the new reference point observed at 550 s. In general, the controller acted relatively fast to counter any disturbances or reference point changes. This aggressive-like behavior was quite favorable to such systems. These systems were not very sensitive to changes or fluctuations; thus, no conservative actions were required for the tank-level system.

Additionally, Figure 3 demonstrates the actuator level with respect to time. As observed in the figure, the actuator level changed at a high rate across small time intervals.

This was a result of the proportional gain of the ZN controller. Additionally, the difference between the reference point and the actual level was eliminated relatively quickly as a result of the integral action.

In comparison between the theoretical plot and the experimental plot, both plots exerted three oscillations. Additionally, the offset was eliminated within 150 s in both the experimental plot and the theoretical plot, as observed in Figures 2, 4, respectively. This observation demonstrated the fast responses of the ZN controller to system disturbances. Furthermore, no differences were observed between the theoretical data and the experimental data.

Figure 5 demonstrates the experimental temperature value versus the HW level. The design technique utilized to control the output response was the ZN technique. The controller gains were 11.45 and 26.4 for the proportional and integral actions, respectively. As observed in the figure, the ZN technique was able to derive the magnitude of the temperature to the reference value at 1,400 s. Nevertheless, as a disturbance was introduced into the system, the controller was not able to minimize its impact on the system response. Additionally, due to the sensitivity of the system, the controller magnified the fluctuations of the temperature readings.

A second ZN controller was implemented at 2,150 s to further examine the response. The controller gains were 1.15 and 92 for the proportional and integral actions, respectively. Although the controller was able to minimize the offset between the reference value and the actual value, it was not capable of completely diminishing the impact of the disturbance. This analysis was conducted after observing the performance of the actuator as seen in Figure 6. Figure 6 demonstrates the level of actuation with respect to time.

As observed in Figure 6, the first ZN controller did not eliminate the effects of the disturbance. Therefore, the second ZN controller was introduced at 2,150 s. As seen at the actuator level, the controller was able to control the disturbance effects. Additionally, the controller was not in a continuous state of on and off, thus suggesting that the second ZN controller was able to control the HW to temperature system better than the first ZN controller.

The main difference between the two controllers was the proportional gain; the P gain magnified the sensitivities observed in the experimental data with respect to the HW to temperature system.

Figure 7 illustrates the performance of the HW to temperature system. The DS method was utilized to obtain the data. The proportional and integral gains were 0.7068 and 140, respectively. As observed in the figure, the temperature reached the reference value as the offset became zero. Additionally, as the disturbance to the system was introduced at 1,700 s, the temperature increased by two degrees and then decreased back to the reference temperature. Although the system was extremely sensitive, the DS technique was able to control the system response. However, the only disadvantage of this system was the fact that it took a lot of time to derive the temperature to the reference value. In elaboration, the system was conservative; however, it was able to get to the desired temperature with no observed fluctuations. Additionally, the performance of the actuator was stable as observed in the appendix with minimal on/off turns.

In a comparison between **Figures 7**, **8**, no overshoots were observed across the two plots. Additionally, the time it took to reach the final value was approximately the same, 500 s, with a small margin of error, ± 30 s. Additionally, the theoretical plot trend can be observed in the experimental data in the time ranges 0–500 and 1,725–2,250 s. Therefore, the DS method utilized to control the HW to temperature was both efficient and realistic.

Finally, the DS technique was utilized to obtain a PI controller for the tank level system. The proportional and integral gains were 0.2493 and 50, respectively. As observed in **Figure 9**, the DS controller was not able to control the tank level efficiently. Oscillations with very long periods were observed. This behavior was not predicted for the tank level system. An oscillating behavior through the DS controller was not supposed to occur. That was because DS controllers were conservative controllers; such controllers were used for sensitive systems to minimize or diminish any possible fluctuations and oscillations. However, oscillations were observed across the CW to tank level system.

A comparison was made between the theoretical data and the experimental data. Both of the plots exerted oscillatory behavior. This observation contradicts the principle of the DS technique in which this method was used to control sensitive systems. Therefore, an assumption was made that the DS technique can also control stable systems; however, this assumption seemed invalid as both the theoretical data and the experimental data stated otherwise.

Figure 10 shows the theoretical CW (cold water) to tank level, and comparing **Figure 8**, an overshoot has been observed. The time taken to reach the final value is 450 s. But **Figure 8** shows that it takes 1,000 s to reach the final value.

Figures 11, **12** show the actuator responses in the MIMO apparatus. **Figure 12** shows the noisy signal from the actuator. **Figure 11** shows some fluctuations in the level.

Conclusion and recommendations

The experiment tested the performance of two techniques to obtain a PI controller for two different systems. The ZN technique was utilized to obtain a PI controller (7) for both the CW to tank level system and the HW to temperature system. Since the CW to tank level system was quite stable, the aggressive-like ZN technique was suitable for the stated system. However, since the HW to temperature system was quite unstable and sensitive, the ZN method was unable to control the output response. Additionally, the ZN technique was able to diminish the disturbance impacts on the CW to tank level system. However, the same technique, ZN, magnified the disturbance impact as the actuator was in a continuous on/off cycle.

The DS technique was implemented on the two systems: the CW to tank level and the HW to temperature. The DS technique was able to control the impact of the sensitive HW to temperature system. However, the controller performance across the CW to tank level system was extremely inefficient as oscillations were observed. Additionally, the time it took for the oscillations to die off was about 1,500 s, which was a disadvantage for the DS technique as it tried to control the stable system. Nevertheless, the conservative technique, DS, was able to control the HW to temperature system effectively and promptly. Furthermore, no oscillations in the output response were observed. Multiple recommendations can be made to improve the performance of the experiment and its learning aspects. Such recommendations are listed as follows: a small mixer must be equipped within the tank for the temperature to be stable. This will minimize the fluctuations observed in the temperature readings. The open-loop coefficients for the ZN method were used. However, the PI controller setup in MATLAB was a closed-loop system; this troubled the students to understand whether the system was an openloop or a closed-loop.

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