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METHODS

System identification and characteristics of multiple input and multiple output (MIMO) water mixing equipment

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Multiple input and multiple output (MIMO) water mixing equipment is a prototype used to study the process control concepts. This equipment is used for manipulating multiple inputs and their effect on the outputs. The input variables are hot water (HW) temperature, cold water (CW) temperature, and flow rate of HW and CW. The output variables are the level of the water in the tank, the temperature of the water, and the flow of outlet water. The changes in controlled variables with the effect of manipulated variables were investigated. The transfer function for the given experimental setup was developed and the time constant for the given system was also developed. These transfer function and analysis of MIMO can be useful for the analysis of various MIMO-based process equipments.

Keywords: controlled variables, manipulated variables, transfer function, time constant and MIMO prototype

Introduction

The multiple input and multiple output (MIMO) water mixing-tank apparatus is an education prototype for studying the fundamental concepts of process control. In this system, there would be many control (output) variables that are affected/controlled/manipulated by several manipulated (input) variables used in a given process. The MIMO water mixing-tank apparatus is illustrated in **Figures 1, 2, 3, 4**. The controlled variables were two water supplies going into the tank, namely, one hot water (HW) inlet and one cold water (CW) inlet. These were controlled with the LabVIEW program. The drain leaving the tank was left in the fully open position throughout the experiment. The measured variables (tank level and water temperature) were measured with the LabVIEW program. The disturbance variables for the system were the temperatures of the inlet streams [HW temperature (Th) and CW temperature (Tc)]. Most industrial control applications involve in MIMO. Modeling MIMO processes is not different conceptually from modeling single-input/single-output (SISO) processes (1).

The objective of this experiment was to identify key system characteristics such as outlet flow, gain, delay, and time constants for MIMO water mixing-tank apparatus. This was done by observing the relationships between CW-to-level, HW-to-level, CW-to-temperature, and HW- to-temperature. These relationships were examined with the LabVIEW program. This program is a graphical programming platform that is useful to scale from design to test and from small to large systems. It is ideal for the measurement of control systems (2). The experimental data were recorded in the Excel format with Data Logger.

This experiment investigates some of the main key characteristics such as the outflow, delay, gain, and the time constant in the system. The experimental setup introduced the concept of controlled systems. The setup contains a large tank that has water in it as well as three manipulated variables. The three manipulated variables are CW, HW, and drain valves. The system characteristics were used to obtain a relationship that relates the level of liquid in the tank and the temperature of the system with step changes in the CW and HW flows. The experiment contains several requirements that were assigned to observe the variations of different degrees of opening valves. The experiment was categorized into 5 different degrees of obstruction of the flow of the valves which demonstrates multiple observations that deal with the height of liquid in the tank as well as the temperature changing due to the abovementioned manipulated variables.

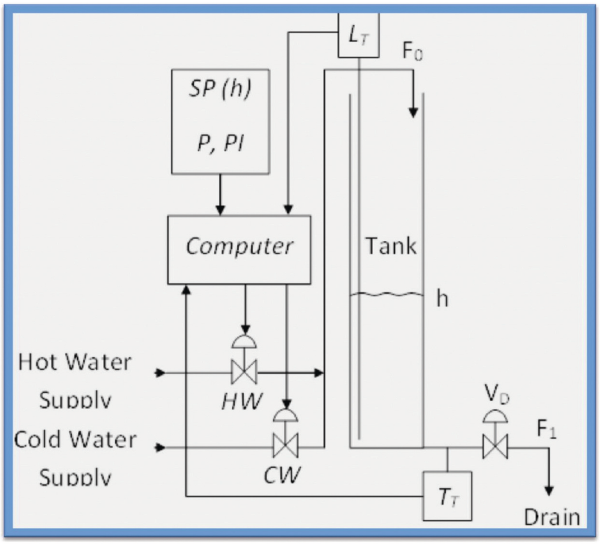

FIGURE 1 | Schematic of the experimental setup.

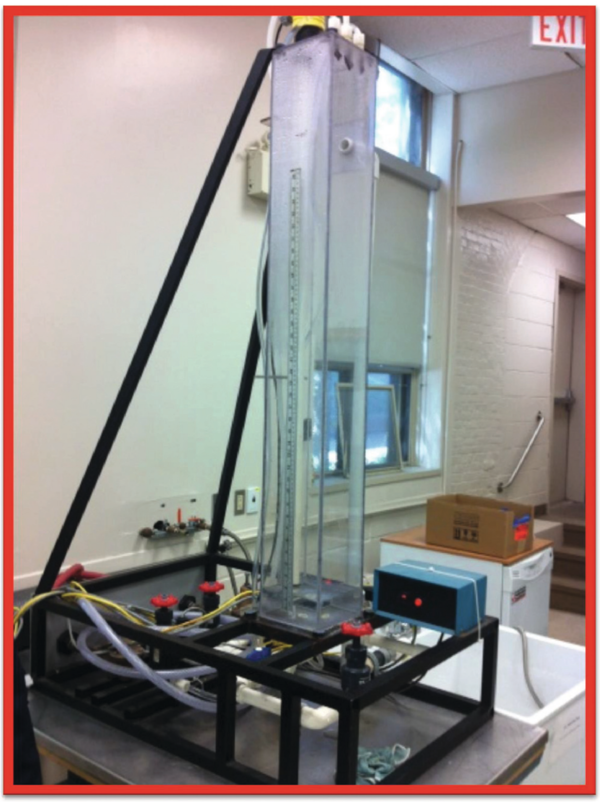

FIGURE 2 | The experimental setup.

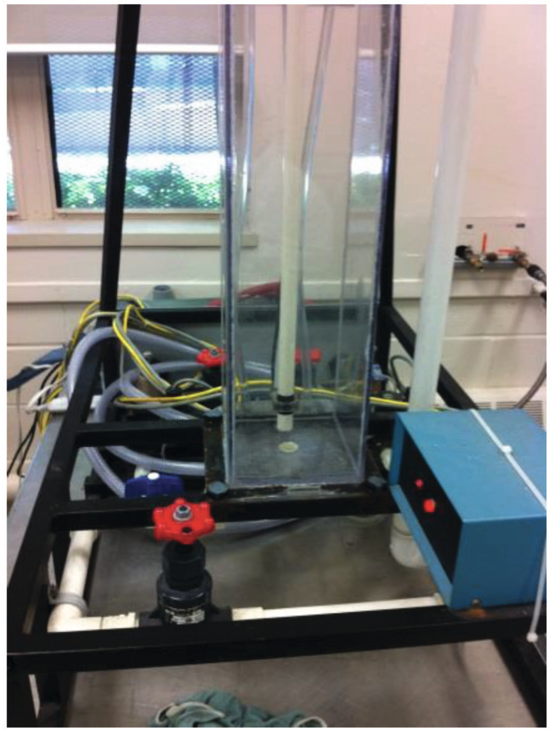

FIGURE 3 | Hot and cold valves.

FIGURE 4 | Drain valve.

In theory, the actuators in the experiment are the valves (hot and cold) that are manipulated to obtain a stable output. The stable output, whether it is the temperature or the height/level of the liquid in the tank, is both plotted on the screen. A step input is inserted through one of the manipulated variables while maintaining the other valve at a fixed value. This is done for the two manipulated variables to produce an output response for each of the MV. The concept of input delay or dead time that occurs in this experiment is specifically concerned with the time required for the output to respond to the changes in inlet variables. Clearly, it is the dead time for a change in the level of liquid in the tank to be observed on the screen. Furthermore, the parameters of interest are the time constant and the gain that are obtained in this experiment and evaluated later on. The time constant represents the time required to reach 63% of the final value or set point (3–5).

This article deals with the system identification and analysis of MIMO apparatus to understand the basic concept of process control and its implementation in the process equipment and to evaluate the transfer function of the MIMO apparatus. In addition to that, the interaction between controlled and manipulated variables in the MIMO apparatus is investigated.

Experimental setup and methods

Experimental procedure

Initially, the tank setup was at a steady state. This was obvious from the leveling of the curve describing the height, h, and the temperature, T, of the tank. The reading on the monitor that correlates the degree of obstruction of the flow of the valves is 0 closed, 1–1/5 opened, 2–2/5 opened, 3–3/5 opened, 4–4/5 opened, and 5 fully opened.

At $t = 0$, the drain valve was fully opened (**Figure 5**) (reading 5 on the monitor), and the readings of cold valve (CV) and hot valve (HV) were 3 and 2, accordingly. The readings of h and T were recorded for this steady state. Then, the CV's reading was manually imputed to 2, while the HV's reading was maintained at 2. Then, a steady state was achieved after about 10 min of waiting time. The steady-state readings of h and T were recorded for this valve's reading. The CV's reading was then maintained with a step change in the HV's reading (3/5). A steady state was achieved and the readings of h and T were recorded. The $t = 0$ configuration was then restored, that is, the readings of CV and HV were returned back to 3 and 2, accordingly. The system was then allowed to achieve a steady state. Then, a step change in the CV to 4 was achieved while maintaining the HV at 2. The steady-state readings of h and T were obtained for this configuration. The system was again returned back to its $t = 0$ configuration and allowed to achieve a steady state. A step input of the HV to 4 was achieved with the CV still at the $t = 0$ reading obtained. At steady state, the values of h and T

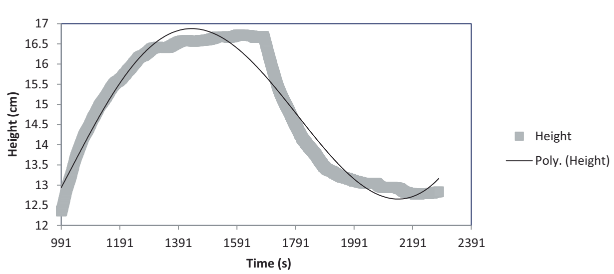

FIGURE 5 | Height vs. time for a step change of CW.

for this configuration were recorded. Finally, the system was returned to its initial ($t = 0$ configuration) state (5).

Results and discussion

The experiment dealt with controlling both the tank level and the temperature of the water tank. The manipulated variables were the CW valve and the HW valve. Through inserting an input signal into the system, the output was observed as it changed from the initial steady-state conditions to the final steady-state conditions. Then, the system was taken back to the previous steady-state conditions in order to simulate the single-step input and observe the output with respect to that input. The data collected for this lab were obtained as a spreadsheet, and multiple figures were obtained in order to calculate the gain of the system, the delay of the response, and the time constant of the output.

Figure 5 represents the tank level output as the system experiences a single input through the CW valve. The input signal is a signal step; therefore, the U(s) term is expressed in the following equation:

$$U(s) = \frac{1}{s} \tag{1}$$

Equation (1) represents the single input signal of the system. The output is considered, for this case, as the water level in the tank. Furthermore, the transfer function for this system is considered the first order since it is a water tank. Moreover, as observed by the curve, the output changes immediately as the input changes. Therefore, the time delay for this step response is zero. The time constant for the transfer function is the time required for the system to reach 63% of its final value. By implementing the final value theorem for this system, the final value is equal to 4.343 cm if we assume that the initial steady-state conditions are set to zero. The 63% of that value is 2.736 cm with respect to the initial steady state. By observing the curve, the time constant that corresponds to (2.736 + 12.356) cm is equal to

$$\tau = 1130 - 991 = 139\,sec \tag{2}$$

Furthermore, the final value theorem represents the MK parameter. While noting that M is equal to 1, then the gain of the system, K, is equal to 3.343 cm. Therefore, the transfer function equation, G(s), is represented as follows:

$$G(s) = \frac{K}{\tau + 1} = \frac{3.343}{139.s + 1} \tag{3}$$

Equation (3) represents the transfer function of **Figure 1**. If it is compared with the MATLAB simulation, the theoretical plot, as shown in **Figure 2**, overlaps with the experimental lab. This strongly demonstrates the accuracy of the transfer function obtained for the system output.

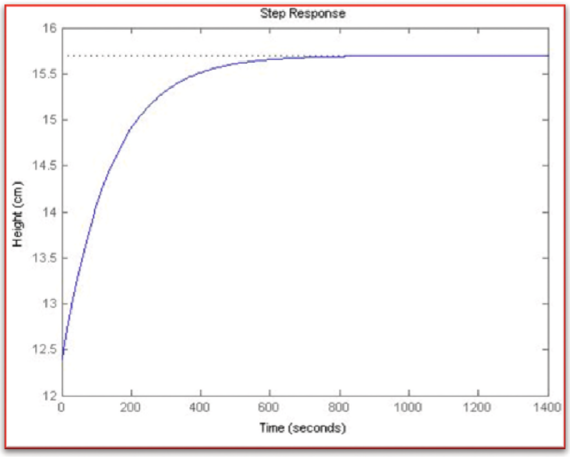

FIGURE 6 | MATLAB simulation with respect to Figure 1.

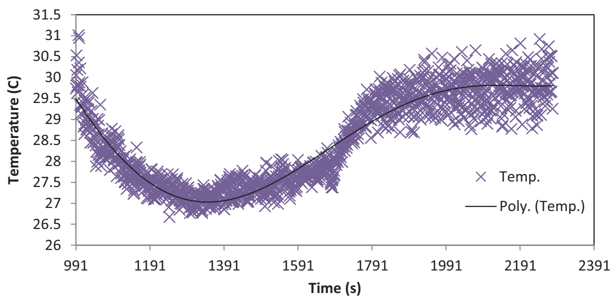

FIGURE 7 | Temperature vs. time for step change of CW valve.

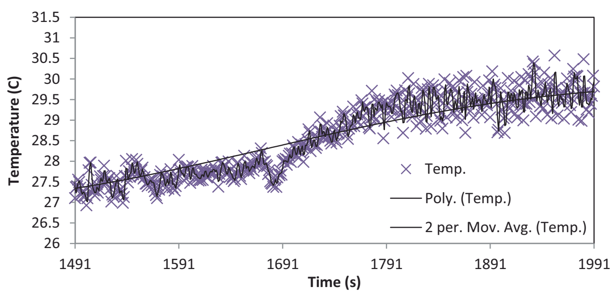

FIGURE 8 | Temperature vs. time for step change of HW valve.

[Figure 7](#) represents the change in temperature with respect to time. The single-step input for this first-order system is the change of flow rate of CW.

As observed in **Figure 3**, the delay of the output response is zero, because the output changed immediately once the input changed. Furthermore, the system gain of the system is represented by the FVT. The FVT, as shown in **Figure 3**, is equal to $-2.825°C$ if the initial conditions are set to zero. Therefore, since the FVT is equal to MK, then K is equal to $-2.825°C$. Furthermore, the time constant represents the time the system takes to reach 63% of the final value. Since 63% of the FVT equals $-1.779°C$, then the time constant is as follows:

$$\tau = (1112 - 991) = 121\, sec \tag{4}$$

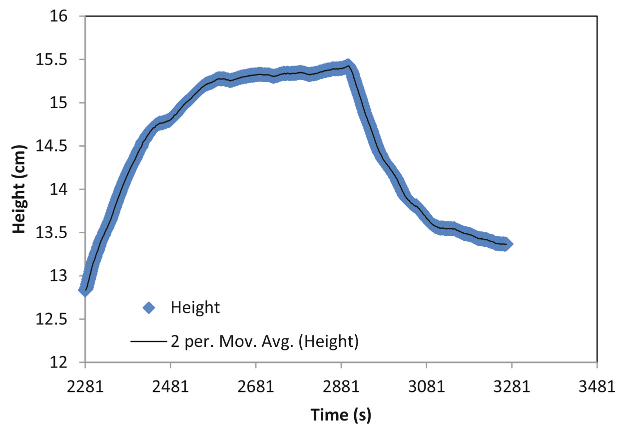

FIGURE 9 | Height vs. time for a single-step change in the HW valve.

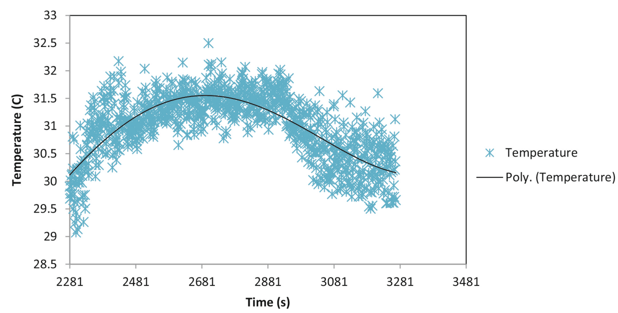

FIGURE 10 | Temperature vs. time for a single-step change in HW.

In addition, the transfer function, G(s), is represented as follows:

$$G(s) = \frac{K}{\tau s + 1} = \frac{-2.825}{121.s + 1} \tag{5}$$

Figure 9 represents the tank level with respect to time. A single input signal represents the U(s) of the system. The output, Y(s), is the tank level. Furthermore, the transfer function, G(s), is considered the first order since the behavior of the output portrays the behavior of the first-order system. The behavior of the output response conveys many futures of the system. The delay, the gain, and the time constant are figured out by recognizing multiple futures of the curve.

Since the output immediately changes as the input function changes, then there is no observed delay with respect to the output response. Furthermore, the gain of the system is represented by the parameter K. Since M is equal to 1 in this scenario, then K is equal to the FVT. Nevertheless, it is essential to nullify the steady-state conditions and set them equal to zero. Once it is done, then the FVT is calculated to be 2.502 cm. Furthermore, the time constant for the output signal is equal to 121 sec. Thus, the transfer function is represented as follows:

$$G(s) = \frac{K}{\tau s + 1} = \frac{2.502}{121.s + 1} \tag{6}$$

Figures 7, **8** demonstrates the relationship between the temperatures of the tank with respect to time. The manipulated variable that is changed in this case is the HW valve. The delay of the response, the gain of the system, and the time constant of the output function are obtained by studying **Figures 7**, **8**. The data for this system are not accurate enough to obtain the required values through visual reading. Therefore, a program called Minitab is utilized in order to obtain the average values with respect to specified time ranges.

The delay of the response, the gain of the system, and the time constant of the output are calculated. The transfer function demonstrates the future of the first-order function. Furthermore, since the input function is as represented in Equation (7), then the FVT is equal to K, since M is equal to 1.

$$U(s) = \frac{M}{s} = \frac{1}{s} \tag{7}$$

Nevertheless, it is required to nullify the initial steady-state conditions and set them to zero. Therefore, the gain of the system, K, is equal to 1.834°C. Moreover, there is no observed delay with respect to the output response; therefore, the delay is set to zero. Furthermore, the time constant of the output function is equal to the time it takes to reach 63% of the final value. Therefore, the time constant is calculated to be 140. From these data, it is possible now to get the transfer function, G(s), for the first-order system as observed in Equation (8).

$$G(s) = \frac{K}{\tau s + 1} = \frac{1.834}{140.s + 1} \tag{8}$$

Since all of the transfer functions obtained represent the first-order systems, then it would be enough to use a proportional, P, controller. That is because overshoots, damping coefficients, and oscillations will not be present in the first-order system, which diminishes the reasons behind using either the integral, I, part or the derivative, D, part.

Conclusion and recommendations

The experiment dealt with the behavior of the controlled variables with respect to the manipulated variables of the system. Furthermore, a mathematical model was required to represent the transfer function of the system. The transfer function, G(s), demonstrated the characteristics of the system. The delays, the gains, and the time constants of the system are calculated for each step change. The transfer functions were obtained along with the parameters for each curve. A comparison is done between the parameters obtained for the different magnitudes of the input signals. This is done in order to eliminate any discrepancies or to determine if there was any present. It is recommended to implement new control devices. A long time constant of 2.33 min was observed. This resulted in longer times in order to achieve the steady-state conditions. It is also recommended to have the drain valve manipulated. This will introduce new behaviors observed into the system and will further enhance the understanding of the control concepts.

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