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Development of IoT based Heat Exchanger Control Trainer for Undergraduate Process Control Programme

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ABSTRACT

Heat exchanger control trainer is a device that helps to demonstrate control of process variables and simulates real world industrial plant system. The implementation of Internet of Things (IoT) technology into the control system allows wireless communication. This paper describes a work to develop an IoT based heat exchanger control trainer for undergraduate process control programme. The control trainer system can implement both Proportional-Integral-Derivative (PID) and fuzzy logic controller. The work was initiated with the development of graphical user interface (GUI) followed by the construction and coding of the control trainer prototype. A heat exchanger control trainer GUI with PID and fuzzy logic controller was developed in this work. Information was able to be transmitted wirelessly between the GUI and control trainer prototype using Wi-Fi modules. The tested maximum signal strength was -90 dBm in 50 m when connected to indoor Wi-Fi router. The control trainer was able to achieve simple temperature feedback control of the cold side of the heat exchanger. The user manual included the basic user guide of the developed control trainer user interface. K_p , K_i , K_d of Ziegler-Nichols tuning method obtained in offline case studies are 90,18, 112.5 whereas for Cohen-Coon tuning method the values are 7.2009, 1.1473, and 7.3163 respectively. The offline test result shows a better accuracy of control using the fuzzy logic controller with -0.07% of steady-state error. Further improvement could be made by adding cooling system into the control trainer prototype and apply modern techniques in the GUI control systems.

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1. Introduction

A process control trainer is a device that helps to demonstrate control of process variables such as temperature, flow, pressure, pH, and level. The process control trainer simulates real world industrial plant systems found in various industries including chemical plants, oil and gas, food industries for a diverse scope of

educational experiences. It is usually designed for users to study physical simulation and complex control systems. Through process control trainers, theory and application, skills and knowledge in installation, tuning, calibration, optimization, maintenance and control of the specific process could be acquired by the trainees. The process control trainer usually consists of mechanical components (such as pump, tank, valve, and heat

a	Triangular function lower limit, °C
b	Triangular function midpoint, °C
c	Triangular function upper limit, °C
g_p	Process gain
K_d	Derivative gain
K_i	Integral gain
K_p	Proportional gain
K_u	Critical gain
PV	Process variable, °C
SP	Setpoint, °C
t	Time, s
T_d	Derivative time, s
t_d	Dead time, s
T_i	Integral time, s
x	Process variable, °C
τ	Time constant, s

exchanger) and electrical components (transmitter and sensor) with a combination of user interface to allow users to view and carry out control actions on the process control device.

A heat exchanger is used to transfer heat from one medium to another through the heat transfer between one or more fluid. Heat exchanger is a highly common equipment that is used in most of the chemical engineering and power facilities (Ranong & Roetzel, 2002). In a heat exchanger control trainer, the main process variable of interest (manipulated variable) would usually be the temperature, in which the process fluid is required to be heated or cooled to a certain temperature set point. The major disturbances that could influence the process fluid outlet temperature are the changes in fluid inlet temperature and fluid flow rate. The control action of fluid temperature in heat exchanger is normally done by controlling the fluid flow rate of the hot or cold stream to achieve a desired set point. Commercial heat exchanger control trainers usually allow users to conduct various studies including study of responses of PID controllers, auto, manual, direct, reverse mode of controllers, PID tuning parameters, and performance of heat exchanger in controlling temperature of the process fluid.

The Internet of things (IoT) is a network of objects ("things") that uses an Internet Protocol (IP) address for internet connectivity. IoT devices can communicate with other IoT devices and other Internet-enabled devices and systems (Javeed, Dhurba, Baig & Samida, 2017). The applications for IoT devices are extensive and it has already in use in various fields such as home automation, media, manufacturing, and healthcare. The IoT enables objects to be sensed using sensor or controlled remotely across existing network infrastructure through wireless network without physical wire connections (Gubbi, Buyya, Marusic & Palaniswami, 2013). Examples of IoT based product include security system, thermostat, health monitor, and car tracking adapter.

The objective of this work is to construct an IoT based heat exchanger control trainer for undergraduate process control programme. The control trainer should be able to monitor process variables and communicate

with the embedded control systems at the user interface through wireless network. The IoT of the control trainer starts at the sensor level where the collected information of temperatures and fluid flow rate are sent wirelessly to the user interface for monitoring and control. PID controller and fuzzy logic controller are included into the graphical user interface. The scope of the work is aimed to be used for undergraduate process control with basic controller design features.

Examples of some of the commercial temperature control trainers are shown in Figure 1 and Figure 2.

Figure 1: Intelitek JobMaster SAPP Process Control Temperature Trainer. (Intelitek, n.d.)

Figure 2: Amatrol's Temperature Process Control Learning System T5553. (Amatrol, 2018)

2. Methodology and Experimental Setup

To develop the heat exchanger control trainer for this study, it involved three major parts: development of control trainer graphical user interface (GUI), development of IoT communication system, and the development of physical control trainer prototype. The user interface for the control trainer was programmed by using the programming language in Visual Basic using the Microsoft Visual Studio. The closed loop control mechanisms applied in the control trainer were PID controller and fuzzy logic controller. The physical components of the control trainer prototype were controlled using Arduino based microcontrollers and these microcontrollers were programmed using the programming language in Arduino IDE. The IoT device for the Wi-Fi module used is NodeMCU. The flow diagram for the steps of coding for the GUI and microcontrollers is shown in Figure 3.

Figure 3: Flow diagram for the GUI and microcontroller coding.

2.1 Development of Heat Exchanger Control Trainer User Interface

The GUI of the control trainer was programmed using Visual Basic under Microsoft Visual Studio. The purpose of the user interface is to develop a platform to allow the user to view process variables and perform control actions toward the offline simulation plant and online control trainer prototype. The parameters that could be controlled by the users in the created GUI were the fluid flow rates of both inlets, set point of heat

exchanger cold side outlet, mode of the control trainer (Online and Offline), and the choice of controllers. The readable parameters were the temperature responses in numerical and graphical forms. The design process was to increase the temperature of the process fluid stream (cold side) through the flow rate control of the service fluid stream (hot side). The schematic flow diagram of the process for GUI is shown in Figure 4.

Figure 4: The schematic flow diagram for the heat exchanger control trainer GUI.

This GUI design was based on the design to simulate the heat exchange process in an industrial plant to heat up or cool down a process stream through the flow rate control. In this study, the control action was on

the hot side of the control trainer and the cold side was remained uncontrolled. Both of the process fluid and service fluid used in this work was water.

Figure 5: GUI layout with toolbox tools label.

The control trainer GUI default window was set up as shown in Figure 5. The GUI was set up to include the control systems of PID controller, fuzzy logic controller, and manual control at the top of the left side of the GUI. The schematic flow diagram was placed at the middle together with corresponding textboxes to show

the process variables of the process. The real-time graph of temperature change for hot side and cold side outlet of the heat exchanger were placed on the right side of the GUI. However, all the individual graphs of the process variables were attainable by double-clicking their corresponding textboxes.

Figure 6: Setup of heat exchanger streams in UniSim Design Suite.

Two modes of operation were designed in the control trainer GUI: Online and Offline Mode. The default mode was set as Offline Mode was the temperature result was based on a simulation file created using Honeywell's UniSim Design Suite as shown in Figure 6. The Online mode was designed to receive the actual data signal from the control trainer prototype and to send control action information to the prototype.

2.2 Control Systems in the Control Trainer Graphical User Interface

For the two controllers programmed in the GUI, PID controller and fuzzy logic controller, both of them were designed as feedback controllers where the control action would be dependent on the error value $e(t)$ between the process variable (PV) and setpoint (SP) as shown in Eq. (1) (Coughanowr & LeBlanc, 2009). The PID

controller applied the PID equation as in Eq. (2) (Coughanowr & LeBlanc, 2009) and the fuzzy logic controller in this process was set up as Eq. (3).

$$e(t) = SP - PV \quad (1)$$

$$u_{pid}(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \quad (2)$$

$$\mu(x; a, b, c) = \max\left(\min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right) \quad (3)$$

2.3 Control Trainer Prototype Setup with IoT System

The IoT based heat exchanger control trainer prototype system was set up to be able to perform communication using Wi-Fi modules. Modification was done for the prototype system due to the constraint of space and resources to make it as four separate process

systems. Therefore, the designed system was slightly different as shown in Figure 4. The control trainer prototype system had hot water and cooling water looping in their storage reservoir instead of coming from or leaving to different systems. The method to control the flow rate in the actual prototype was using pump motor speed control using pulse-width modulation (PWM) instead of flow controller. The simplified P&ID of the control trainer prototype is shown in Figure 7. In this control trainer prototype system setup, it consisted of one cooling water supply and one hot water supply from their respective reservoirs. Each of the water source circulates independently in their loops without mixing but exchanging heat through the braced plate heat exchanger at the middle.

Figure 7: Simplified P&ID of the control trainer prototype system.

The main physical components involved in the control trainer prototype setup is shown in Table 1. Other auxiliary components such as PVC pipes, water tanks, coil heating element, wiring, and fittings are not listed as they can be customized according user needs.

Table 1: Major components used for the hardware setup.

Component	Model/Type	Quantity
Heat exchanger	Braced plate heat exchanger (22.55 kW)	1
Pump	12V water pump	2
Thermocouple	MAX6675 K-type thermocouple	4
Flow meter	Water Flow Sensor YF-B2	2
Microcontroller	Arduino Mega	1
Microcontroller	Arduino Uno	1
Wi-Fi module	NodeMCU ESP8266	4
Motor driver	Adafruit Motor Shield L293D	1

The detailed setup of the control trainer prototype system is shown in Fig. 8. From the figure, it could be seen that all the sensors (flow meters and thermocouples) were connected to one microcontroller (Arduino Mega) and microcontroller was connected to one Wi-Fi Module. This setup allows the information of the process (temperature and flow rate) to be sent from the prototype to the data centre (computer) remotely and wirelessly. For the flow control of the hot side of the heat exchanger, the pump motor speed control was achieved by using motor driver that connected to a microcontroller

(Arduino Uno). This microcontroller also connected to one Wi-Fi module to receive the signal from the data centre. The signal of the pump motor speed was decided by the control system in the GUI depending on the set point of the operation. There are two Wi-Fi modules connected to the data centre separately, each of them is responsible to the sensor and pump system respectively.

2.4 PID Controller Tuning

The PID coefficients of the controller were obtained using Ziegler-Nichols (Z-N) tuning method and Cohen-Coon tuning method for closed loop and open loop control respectively.

2.4.1 Ziegler-Nichols Tuning Method

In the Z-N tuning, the I (integral) term and D (derivative) term of the PID controller was first turned off. The three PID terms (K_p , K_i , K_d at (c)) were initially set to zero. The gain of the proportional controller K_p (K_p) was slowly increased from zero, the output of the controller (temperature displayed by TT03) was observed. The K_p was increased until the output exhibited sustained oscillations on the set point and the critical gain, K_u and the period of the oscillation frequency at the stability limit, T_u were obtained. After obtaining the K_u and T_u values, the K_p , T_i and T_d terms were obtained as according to the coefficients suggested for the Ziegler Nichols method (Ziegler & Nichols, 1942).

Figure 8: Schematic diagram for the hardware setup.

2.4.2 Cohen-Coon Tuning Method

For the C-C tuning, the control trainer GUI was first set in Manual Mode. Speed 4 (0.2 m³/h) was selected and the controller was allowed to run and the process was waited to be stabilized. A step change of was made at the controller output, CO (i.e. FT01 flow rate) by choosing Speed 1 (0.8 m³/h) and waited for the process variable, PV (i.e. TT03 temperature) to settle out at a new value. After obtaining the step change graph, the total change obtained in PV and change in CO was converted to a percentage of the span, then the process gain, g_p was calculated by using the Eq. 4.

$$g_p = \text{change in PV [\%]} / \text{change in CO [\%]} \quad (4)$$

On the PV response curve, the maximum slope at the inflection point in which the PV stops curving upward and begins curving downward was found. A tangent line to the PV curve through the point was drawn and the line was extended to intersect with the original level of the PV. From the graph, the dead time (t_d) was obtained as the difference in time between the change in CO and the intersection of the tangent line and the initial PV level. The value of the PV at 63% of the total change was obtained and time value on the graph at which the PV reaches 63% of the total change was obtained. The time constant τ (tau) was obtained as the difference in time between the time PV reaching 63% of its total change at the end of dead time (t_d). After obtaining g_p , τ , and t_d , the PID terms were calculated using the Cohen-Coon tuning method coefficient (Cohen & Coon, 1953).

3. Results and Discussion

3.1 Development of IoT based Heat Exchanger Control Trainer Prototype

The heat exchanger control trainer prototype was constructed as shown in Figure 9. The hardware components setup was developed according to the setup

shown in Figure 7 and the electronics setup was based on the setup shown in Figure 8.

The constructed heat exchanger control trainer prototype was able to exchange heat between the cold side and hot side of the heat exchanger as planned. The control and monitoring of the IoT based prototype was able to be achieved using Wi-Fi modules. Control actions could be sent from the data centre (computer) to the motor driver connected to the pump through wireless network using Wi-Fi under local network. The control action of the prototype was determined by the signal sent by the control system in the control trainer graphical user interface. The data signal of temperatures and pressure could also be obtained wirelessly from the sensors to the computer and be displayed in the graphical user interface.

Figure 9: Heat exchanger control trainer prototype with labels (top view).

3.1.2 Prototype Test for controller

Tests were carried out to test the performance and functionality of the heat exchanger control trainer prototype. Three major tests were carried out for the PID controller with Ziegler-Nichols (Z-N) and Cohen-Coon (C-C) parameters, and fuzzy logic controller.

(a) Online Test with PID Controller (Ziegler-Nichols Tuning Coefficients)

In the test, the GUI was set in Online Mode and the controller was set to PID controller with PID coefficients obtained from Ziegler-Nichols (Z-N) tuning method shown in the Table 4. The PID coefficients of K_p , K_i , K_d were set as 90, 18, 112.5 respectively. The setpoint for TT03 was 40°C. The result is shown in Figure 10.

Figure 10: Response for Online temperature control test with Z-N tuning.

(b) Online Test with PID Controller (Cohen-Coon Tuning Coefficients)

In this test, the PID coefficients were set as obtained from Cohen-Coon (C-C) tuning method shown in the Table 4. The PID coefficients of K_p , K_i , K_d were set as 7.2009, 1.1473, 7.3163 respectively. The set point for TT03 was 40°C. The result is shown in Figure 11.

Figure 11: Response for Online temperature control test with C-C tuning.

(c) Test with Fuzzy Logic Controller

In this test, fuzzy logic controller was used to reach the setpoint. The set point for TT03 was 40°C. The result the result is shown in Figure 12.

(d) Discussion of Control Trainer Online Result

The combined results of Ziegler-Nichols, Cohen-Coon, and fuzzy logic case studies for Online Mode is shown in Figure 13 and Figure 14.

From Figure 13, it shows that the Online test have relatively similar results in the temperature response using different controllers. The temperature increases initially until overshooting the set point at 40°C and then remains relative constant over time. The results show that the control trainer was functional to control the process fluid to a certain temperature according to

the setpoint. As the Z-N method has the highest gain, the increase and decrease of the pump motor speed to the maximum and minimum are the fastest, followed by C-C method and fuzzy logic controller, as shown in Figure 14.

Figure 12: Graph of response for temperature control test with fuzzy logic controller.

This result also shows the limitations of the constructed prototype in many ways. One of the limitations is the control of motor speed of the pump. Motor speed control of the pump has its limitation in changing speed. The pumps used in the prototype also have low quality to perform such rigorous speed change. Besides, there were only 4 speeds available in this control trainer prototype system. Therefore, the change in water flow rate was a step change rather than a gradual change. The flow meters used also has limitation in its weak sensitivity to detect the change in flow rate of the system if the changes are not significant. In most cases the detectable flow rate change is from 0-3 m³/h with 1 significant figure of sensitivity. Due to these limitations in both pump motor speed and flow meter sensitivity, from Figure 14 it could observe that the step changes in flow rate occur.

Another critical limitation of the control trainer prototype is the lack of cooling system. As the cooling water is circulating through the heat exchanger, the temperature of the water in the reservoir increases gradually. The cooling water reservoir is not large enough to omit the change in temperature. This causes the cold side temperature of the control trainer prototype could only increase but could not decrease significantly, as shown in Figure 13. Therefore, the control trainer could not drop to a temperature very close to the setpoint after overshooting the setpoint. Improvements could be made by either adding cooling system with radiator or separate the cold inlet and outlet system and do not loop the water in the same reservoir.

3.1.3 Application of IoT

The control trainer successfully applied the IoT technology in achieving wireless information transfer. The information transferred includes the data information of temperatures and flowrates from the control trainer prototype, as well as the signal from control trainer user interface to decide the pump motor speed remotely. To determine the connectivity of the control trainer, tests were carried out using indoor Wi-Fi router to test the longest distance and the strength that

the control trainer could transfer information using IoT devices. The result is illustrated in Table 2.

From the test, it could be observed that when the distance reached 50 m and the signal strength reached -90 dBm, the connection between the control trainer at the data centre and the transmitters of sensors was broken. In the test it was also found that as long as the

transmitters were connected to the wireless network, the connection stability was almost equally good although the distance between the data centre and the transmitters increased. The mentioned good stability means that the control trainer at the data centre could receive a stable data from the control trainer sensors every 1 second, same as the programmed setting.

Figure 13: Temperature response of Z-N, C-C, and fuzzy logic Online case studies.

Although the finding was tested with increasing distance, the actual factor that determines the connection between the transmitters and wireless connection is the signal strength. This signal strength varies from router to router, and in indoor condition, the obstacles present

would also weaken the signal strength. Therefore, the result obtained in Table 2 is also dependent on the signal strength of the router, which the result would differ if connected to a different Wi-Fi hotspot.

Figure 14: Flow rate response of Z-N, C-C, and fuzzy logic Online case studies.

3.2 Implementation of PID and Fuzzy Logic Controller

Both PID controller and fuzzy logic controller were applied into the developed GUI to perform the control action. Tests were carried out in the Offline Mode

where the response was based on the simulation file created using Honeywell UniSim Suite. The combined results are shown in Figure 15 and Figure 16.

Figure 15: Combined temperature response for Offline case studies.

Figure 16: Combined flow rate response for Offline case studies.

Table 2: Distance of information transfer of control trainer with signal strength.

Distance (m)	Signal strength (%)	Signal strength (dBm)	Connection	Stability
1	100	-22	Yes	Good
5	83	-59	Yes	Good
15	60	-63	Yes	Good
20	50	-75	Yes	Good
30	48	-82	Yes	Good
50	42	-90	No	N/A

Note. The signal strength was tested using Wi-Fi strength mobile app.

Figure 15 shows that all case studies have relatively similar responses in the temperature control. In general, the temperatures increase until they overshoot the setpoint at 60°C, and then they reach their peak temperature. After that, the temperatures start to decrease and then they stabilize and reach a steady-state where they oscillate around or close to the setpoint. The temperature response for C-C tuning shows the greatest overshoot, followed by fuzzy logic controller, and Z-N tuning. Both of the C-C tuning and fuzzy logic controller shows a more accurate result, where the steady-state result oscillate slightly around the setpoint at 60 °C. The response from Z-N tuning although illustrated the least overshoot, but the steady state result is undershooting below the setpoint and it has the highest steady-state error. The summarized result between these 3 case studies is shown in Table 3.

Table 3: Comparison of result for Z-N, C-C, and fuzzy logic case studies.

Case Studies	Overshoot (°C)	Rise time (s)	Peak time (s)	Settling time (s)	% Overshoot (%)	Steady-state temperature (°C)	Steady state error (%)
Z-N	60.5	28	29	44	0.83	59.15	-1.42
C-C	61.7	27	29	35	2.83	59.93	-0.12
Fuzzy Logic	61.3	27	29	34	2.17	59.96	-0.07

Note. The time is based on the application of setpoint at $t = 9$ s

The fuzzy logic case study shows a better performance compared to the PID controller with shortest settling time and the least steady-state error of -0.07%. The test with Z-N tuning shows the highest steady-state error of -1.42%. Other parameters such as the rise time and peak time were relatively similar in all the case studies. The fuzzy logic controller does not require tuning like the PID controller does, in which the error in tuning could be reduced.

In Figure 16, it could be observed that the change in flow rate is more abrupt in Z-N tuning case study. This is because of the high gain of the controller. However, as the maximum flow rate in this controller system was set only until 0.8 m³/h, the differences are not apparent in this high gain. If without setting the limitation of flow rate, in real cases the pump motor could eventually run until failure if the supply voltage supplied by the motor driver keeps increasing.

Table 4: Summary of Z-N and C-C tuning coefficients from Offline case studies.

Tuning Method	Kp	Ti	Td	Ki	Kd
Z-N	90.0000	50.0000	1.2500	18.0000	112.5000
C-C	7.2009	6.2763	1.0161	1.1473	7.3163

Note. $K_i = K_p / T_i$ and $K_d = K_p T_d$

As Z-N tuning and C-C tuning are not necessarily suitable for all systems, the C-C tuning result for PID controller in this control trainer shows a better result with a less steady-state error. The PID tuning result from Z-N method in this control trainer may be less accurate as the gain K_p obtained is too high compared to C-C method. During the tuning Z-N tuning of this control trainer, the proportional gain was increased until very high in order to obtain the sustained oscillation with constant period. This may indicate that the Z-N tuning method may not be suitable to apply in this control trainer system. The high gain would result in abrupt change in the controller output. Limitations may exist in the developed coding in the response to imitate the dynamic temperature change in the real system. Therefore, less differences in temperature response could be observed using the dynamic mode of the GUI.

3.3 Open Loop and Closed Loop Tuning for PID controller

Open loop and closed loop tuning for PID controller was carried out in the Offline Mode of the control trainer GUI. The open loop tuning was using the Cohen-Coon (C-C) tuning method whereas the closed loop tuning was using Ziegler-Nichols (Z-N) method. The tuning result is shown in Table 4.

4. Conclusion

The development IoT based of heat exchanger control trainer framework for undergraduate study was successfully in which the basic control of temperature and communications between the data centre and the heat exchanger prototype for the information control action and temperature and flow rate data could be achieved. The developed heat exchanger control trainer included both physical prototype together with the graphical user interface to perform the control as well as

receive the sensor data wirelessly through the application of IoT technology. The test shows that the IoT system under the current setup could be still functional in the range of less than -90 dBm. PID and fuzzy logic controller were implemented into the control trainer graphical user interface and they function as the control mechanisms for both Online and Offline control. A classical PID control system and a fuzzy logic controller with single input was converted into codes that are applicable to be used in Microsoft Visual Basic. The user manual demonstrated a user guide to use the control trainer, as well as the open loop and closed loop tuning method. From the Offline case studies, the PID coefficient of K_p , K_i , K_d obtained for the Ziegler-Nichols tuning was 90, 18, 112.5 respectively whereas for Cohen-Coon tuning method was 7.2009, 1.1473, 7.3163 respectively. The Offline case studies comparing the PID and fuzzy logic controller shows that the fuzzy logic controller is slightly better performance than the PID controller, with 2.17% overshoot and -0.07% steady-state error.

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