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Cyber-Physical Systems-Based PID Controller for Three Interacting Tank Process Level Control

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Abstract. This paper considers the performance improvement of PLC-based process control systems through Industry 4.0 by harnessing cyber-physical systems (CPS), which is an integration of control, computation, and networking to intertwine intensely cyber and physical components. To accomplish these needs, open process control (OPC) unified architecture (UA) is exercised as a horizontal and vertical integrator of the CPS-based process automation. The three interacting tank process is the preferred testing plant because this system has become a proven benchmark for testing advanced control system in the laboratory scale. In this paper, the cyber component accomplishes parameter optimization of the PID controller for the level control of the three interacting tank process and schedules the appropriate PID controller that matches the level operating conditions. The control implementation shows that CPS for the level control of the three interacting tank process works well by resulting in smaller integral square error (ISE) value. Moreover, the cloud-based database can be established directly using OPC UA for real-time monitoring of the process through websites using the Internet network with data delivery rate of 100%.

1. Introduction

The development of industries in the world until now has reached the Fourth Industrial Revolution known as Industry 4.0. The main idea of this revolution is to exploit the potential of new technologies and concepts such as the use of the Internet and the Internet of Things (IoT), the integration of technical and business processes in corporations, real-world virtualization, and the presence of smart factories [1], [2]. The machines in factories with Industry 4.0 can visualize the entire production process and make decisions independently because they are equipped with sensors including wireless connectivity. The technology base is the intelligent automation that intertwines of virtual and physical systems known as cyber-physical systems (CPS) with a decentralized control system that is connected to the Internet. CPS allows the industries to have customization of products and flexibility in production quantities. Systems based on Industry 4.0 have a more favorable system response [3-9]. Furthermore, the Fourth Industrial Revolution comprises areas which are not generally classified as an industry, for instance, smart cities.

Today, the industry, in some senses, is in transition from the third to the fourth era. In the third industrial era, the products produced are more flexible and can be made custom by using



programmable logic control (PLC) which can be programmed based on relay ladder diagram or distributed control systems (DCS) in process industries. However, production in the process or manufacturing industries is currently driven by increasingly competitive global competition, the need for rapid production adaptation to changing market demands, and customization of customer wants. Therefore, the production system requires decentralized control and has easy connectivity for real-time exchange of information with the aim of identifying, finding, tracking, monitoring, and optimizing the production process based on the analysis of that information [2]. In this regard, one of the challenges that arises is how to use PLC or DCS that has been proven in the industry to answer these challenges and to follow the direction of the advancement of Industry 4.0 by means of the brownfield integration.

The paper describes the implementation of Industrial 4.0 design in a three interacting tank plant as a medium for probing the basic concepts of Industry 4.0-based system architecture on a laboratory scale. The three interacting tank process is decided because this system has often been used as a benchmark for the design of advanced control systems [10-12]. The dynamics of the three interacting tank system that is nonlinear and has a delay time provide high complexity and difficulty as a challenge in control system designs. The focus of attention is on the design of CPS that involves entwined physical and virtual systems to achieve the objective of industrial process automation performances.

2. Cyber-physical systems

2.1. CPS and IoT

CPS is a collaboration of elements of control, computing, and communication that integrates physical components, each working on distinct spatial and temporal scales [3-9]. The system can improve the ability of physical process systems by combining them with the power of computing systems and data exchange through communication whether wired or wireless. Generally, the CPS structure has three main parts, namely, a real plant, a computing platform, and a network. The real system as a physical part of CPS includes mechanical parts, chemical or biological processes, or human operators. Computing platforms then generally consist of sensors, actuators, computers, and operating systems. Meanwhile, the network provides a mechanism so that computers can communicate with physical objects. The computing and network platforms form a cyber part of CPS.

Meanwhile, the Internet of Things (IoT) is a codependent concept between computers, machines, sensors, objects, and humans with distinctive identifiers capable of sending and receiving data throughout networks with no human intervention [13-15]. For the meantime, the Industrial Internet of Thing, commonly called IIoT, is a concept that connects all hardware and software in the industrial environment so that it can be seen by all operations anytime and anywhere by utilizing the Internet network. It is an infrastructure of interrelated objects, people, systems, and information sources together with intelligent assists to let them manage information from the physical and the virtual world and respond [16]. According to the Picasso definition [17], IoT is seen as an empowering technology for CPS or CPSoS (CPS of systems). The integration of IoT and CPS into closed-loop, real-time IoT-enabled cyber-physical systems is seen as an important future challenge.

The concept of Industry 4.0 enables fast and dynamic production that requires appropriate networks and communication between devices and services with the ability to communicate directly with each other. Sensors, gauges, RFID chips, PLC controllers, human-machine interfaces (HMI), manufacturing execution system (MES), and enterprise resource planning (ERP) systems all provide important production data for the company. In conventional control architectures, data requests are driven by events or are started cyclically and always respond to requests from above (higher level) in the hierarchy of an industrial automation system, as shown in figure 1, i.e., from the client level. The lower level always acts as a server and responds, to illustrate, visualization, can request status data from the PLC, or transfer new production recipes to the PLC. The first step is the conversion of electrical sensor signals into digital information followed by the time stamp allocation of the PLC and sending information to the MES information technology level through further services [18], [19].

In general, according to [10], all communication scenarios and use cases defined in Industry 4.0 and IoT groups can be distinguished from abstract perspectives into two architectural contexts of communication, namely, services in hard real-time context, i.e., the context of automation by means of deterministic PLCs for control purposes, and services in soft real-time context, i.e., in the IT context. In this perspective, determinism can be seen as quality of service (QoS) with certain requirements that can be met by a process communication. This requirement will be determined by the guaranteed duration, for example, 100 μ s response time. In IoT and Industry 4.0, communication will no longer be based on pure data and data communication interoperability but on the exchange of information models, that is, semantic interoperability. Important factors are the integrity of transmission and the security of access rights to individual data or services. All these requirements are relied on OPC unified architecture (OPC UA). It contains a description language and communication services for information models. Thus, the PLC can horizontally exchange complex data structures with other controllers or call methods vertically on the OPC UA server in an MES/ERP system, to illustrate, to take new production orders, or to write data to the cloud. This allows the production line to act independently, as shown in figure 1 [20].

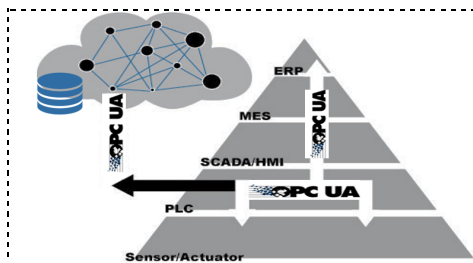


Figure 1. Vertical and horizontal integration in the automation hierarchy

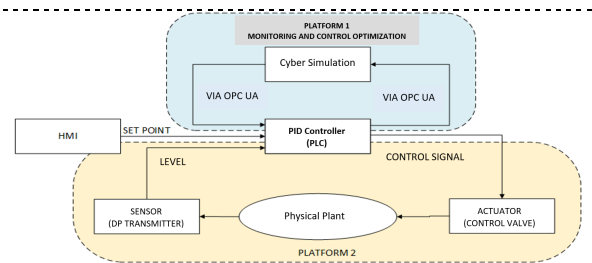


Figure 2. The CPS structure of a three interacting tank system

2.2. Cyber-physical system modeling

CPS development is performed in stages starting from system modeling, simulation design, and analysis of simulation results. Figure 2 displays the structure used in implementing CPS on a three interacting tank system. Platform 1 in the upper part, the cyber part of CPS, is computational on a computer in the form of simulations to monitor operations on real plants and to optimize PID control using a PLC according to a simulated system model, while Platform 2 in the lower part is a physical component of the CPS system that consists of a PLC controller, a level sensor, and an actuator in the form of a motorized control valve. These two platforms run together in hard and soft real-time so that the optimization results from the cyber system can be directly implemented to the physical system. Data communication using OPC UA makes it possible to exchange data between MATLAB Simulink software with PLC, as shown in figure 3.

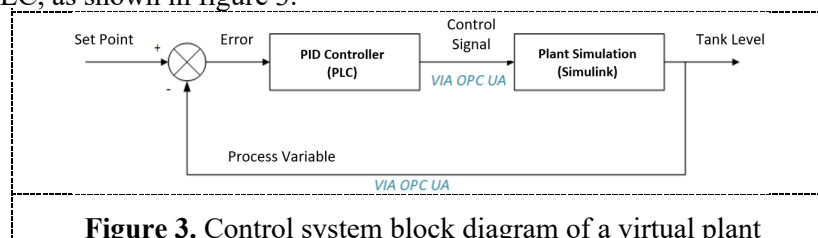


Figure 3. Control system block diagram of a virtual plant

2.3. Three interacting tank system

Figure 4 shows the system diagram of the three interacting tank system. The output variable is the level in the third tank, and the input variable is the fluid inlet flow in the first tank. The mathematical equation of the three-tank system with interaction is known to be nonlinear and has a delay time, so it is often used as a benchmark for advanced control system designs [10-12]. In this paper, a state space-

based PID controller [21] is designed using the linear quadratic regulator method [22], [23]. The dynamic equation of the three-tank system is linearized at several operating points.

The general equation in a tank and the turbulent flow equation in a valve are

$$\frac{dV(t)}{dt} = q_{in}(t) - q_{out}(t) \quad q = Cd \cdot a \cdot \sqrt{2g\Delta h} \quad (1)$$

From the three interacting tanks, there are three equations, namely,

$$\frac{dh_1(t)}{dt} = \frac{q_{int}(t)}{A_1} - \frac{Cd_1 \cdot a_1}{A_1} \sqrt{2g(h_1(t) - h_2(t))} \quad (2)$$

$$\frac{dh_2(t)}{dt} = \frac{Cd_1 \cdot a_1}{A_2} \sqrt{2g(h_1(t) - h_2(t))} - \frac{Cd_2 \cdot a_2}{A_2} \sqrt{2g(h_2(t) - h_3(t))} \quad (3)$$

$$\frac{dh_3(t)}{dt} = \frac{Cd_2 \cdot a_2}{A_3} \sqrt{2g(h_2(t) - h_3(t))} - \frac{Cd_3 \cdot a_3}{A_3} \sqrt{2gh_3(t)} \quad (4)$$

The notations for equations (1) to (4) are defined as V, volume; q_{in} , input flow rate; q_{out} , output flow rate; h_i , tank level; Cd_i , coefficient discharge; a_i , valve cross-sectional area; and $i=1,2,3$. From the three-tank equations, the equation is linearized using Taylor's series, and then the state space matrix is made using the Jacobian matrix, obtained

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \quad (5)$$

with matrices A, B, C, and D as follows:

$$A = \begin{bmatrix} -\frac{Cd_1 a_1}{A_1} \frac{g}{\sqrt{2g(h_{1o} - h_{2o})}} & \frac{Cd_1 a_1}{A_1} \frac{g}{\sqrt{2g(h_{1o} - h_{2o})}} & 0 \\ \frac{Cd_1 a_1}{A_2} \frac{g}{\sqrt{2g(h_{1o} - h_{2o})}} & -\frac{Cd_1 a_1}{A_2} \frac{g}{\sqrt{2g(h_{1o} - h_{2o})}} - \frac{Cd_2 a_2}{A_2} \frac{g}{\sqrt{2g(h_{2o} - h_{3o})}} & \frac{Cd_2 a_2}{A_2} \frac{g}{\sqrt{2g(h_{2o} - h_{3o})}} \\ 0 & \frac{Cd_2 a_2}{A_3} \frac{g}{\sqrt{2g(h_{2o} - h_{3o})}} & -\frac{Cd_2 a_2}{A_3} \frac{g}{\sqrt{2g(h_{2o} - h_{3o})}} - \frac{Cd_3 a_3}{A_3} \frac{g}{\sqrt{2g(h_{3o})}} \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{A_1} \\ 0 \\ 0 \end{bmatrix} \quad C = [0 \ 0 \ 1] \quad D = [0]$$

where h_{1o} , h_{2o} , and h_{3o} are the equilibrium points of the differential equations.

The dimensions of each tank are 14 cm × 14 cm × 100 cm, which are connected using pipes and water taps. The sensor used is the differential pressure (DP) transmitter to measure the pressure at the bottom of the third tank as a level indicator, while the actuator used is a motorized control valve of ball valve type with an input signal in the form of 4–20-mA current which moves the control valve to the desired opening. Control and data acquisition are done using a PLC. The purpose of controlling this plant is to set the level of the third tank by changing the input water flow. The input water flow is adjusted according to the control valve opening. The following figures are the piping and instrument diagram (P&ID) and the level control system design in figure 4a and 4b.

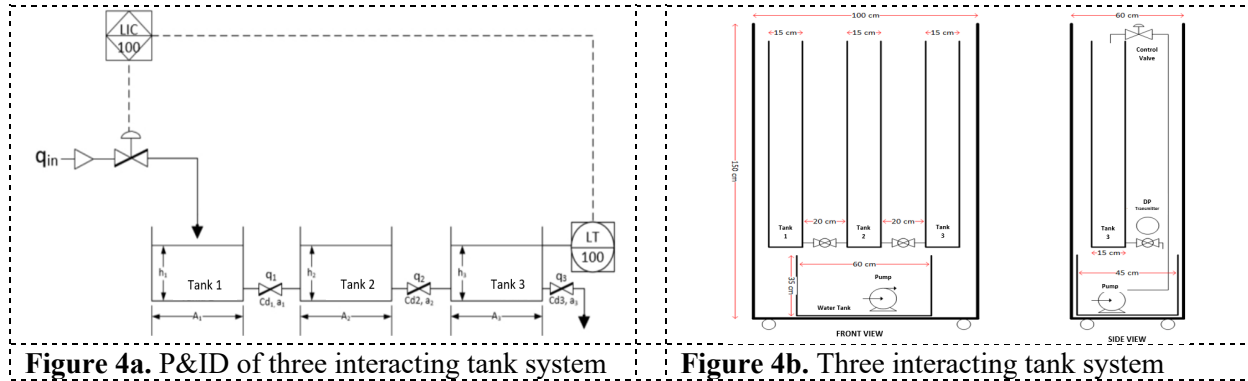


Figure 4a. P&ID of three interacting tank system

Figure 4b. Three interacting tank system

Data collection of control valve characteristics is manually done by adjusting the valve opening with a range of 5%, while the measurement of water discharge is manually done by calculating the volume of water and the time required to reach that volume. The experimental results show that the control valve characteristic is a quick opening with small changes in valve opening which will result in large changes in discharge. Level sensor calibration (DP transmitter) is done by comparing the current reading value on the PLC with the tank level measured manually using a ruler. The results show that the DP transmitter response is quite linear and has a hysterical response for an up and down response. It has a minimum hysteresis of 0.02 at the level of 70 cm and a maximum hysteresis of 0.046 at 5 cm. The results of these data show that a scaling on the PLC program from 4.05–8.5 mA was converted to a level scale from 0 to 70 cm.

2.4. Tuning PID with LQR

PID tuning method based on state space equations used in the paper is to use LQR (linear quadratic regulator). The PID controller design is represented as full-state feedback in the control law [22], [23]. The following is a linear time invariant system with a single input single output described in state space equations:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + B_1 u(t) \\ y(t) &= Cx(t) \quad x = (0)\end{aligned}\quad (6)$$

Let the system in equation (6) then proceed with the definition of the standard PID controller output function [23] denoted by $u(t)$, as well as the input of the PID denoted by $y(t)$ is given by

$$u = k_1 \int_0^t y dt + k_2 y + k_3 \dot{y} \quad (7)$$

where $k_1 = K_p / T_i$, $k_2 = K_p$, and $k_3 = K_p T_d$ with K_p , T_i , and T_d are proportional gain, integral time parameters, and time derivative parameters of the PID controller, respectively. Equation (7) is then expressed as a full-state feedback by using Equation (6) with the notation \hat{K} denoted as normalization of $K = [k_1 \ k_2 \ k_3]$:

$$\hat{K}^T = [\hat{k}_1 \ \hat{k}_2 \ \hat{k}_3]^T = (1 - k_3 C B_1)^{-1} [k_1 \ k_2 \ k_3]^T \quad (8)$$

The control signal equation $u(t)$ in the form of derivatives is given by

$$\dot{u} = \hat{K}^T \begin{bmatrix} C^T & A^T C^T & (A^2)^T C^T \end{bmatrix}^T x + \hat{K}^T \begin{bmatrix} 0 & B_1^T C^T & B_1^T A^T C^T \end{bmatrix}^T \quad (9)$$

then defined K_x and K_u as follows:

$$K_x = \hat{K}^T \begin{bmatrix} C^T & A^T C^T & (A^2)^T C^T \end{bmatrix}^T \quad K_u = \hat{K}^T \begin{bmatrix} 0 & B_1^T C^T & B_1^T A^T C^T \end{bmatrix}^T$$

The PID controller (7) to (9) consists of state feedback in the upper loop and a backstepping integrator in the lower loop [23]. Equation (9) is the output of feedback that uses the feedback state constraint. The control signal equation (7) can then be written as follows:

$$u_a = K_a^T x_a$$

$$\text{where } u_a = \dot{u}, \quad x_a = \begin{bmatrix} x \\ u \end{bmatrix} \text{ and } K_a = \begin{bmatrix} C^T & A^T C^T & (A^T)^2 C^T \\ 0 & B_1^T C^T & B_1^T A^T C^T \end{bmatrix} \hat{K} = \Gamma \hat{K} \quad (10)$$

thus, the augmented state space equation is as follows:

$$\dot{x}_a = A_a x_a + B_a u_a \quad ; \quad A_a = \begin{bmatrix} A & B_1 \\ 0 & 0 \end{bmatrix} \quad B_a = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (11)$$

PID parameter values are obtained by getting the \hat{K} matrix. The search for \hat{K} requires the full-state feedback K_a matrix for the augmented system (11) which is a solution of the linear quadratic equation (LQR) method by solving the following algebraic Riccati equation (ARE) (12) [22]:

$$A_a^T P + P A_a - P B_a R^{-1} B_a^T P + Q = 0; \quad Q \geq 0 \text{ and } R > 0 \quad (12)$$

The gain state feedback matrix is $K_a = R^{-1} B_a^T P$ after getting P that minimizes the quadratic cost (J):

$$J = \frac{1}{2} \int_0^\infty (x_a^T Q x_a + u_a^T R u_a) dt \quad (13)$$

The closed-loop system $\dot{x}_a(t) = [A_a - B_a K_a] x_a(t)$ is guaranteed asymptotically stable if and only if the triple pair $\{A_a, B_a, C_a\}$ is minimal realization [22], [23].

3. System design and manufacture

3.1. System architecture design

The designed CPS architecture consists of several subsystems including the plant in the form of a three interacting tank process controlled using Allen Bradley ControlLogix 5573 processor series as PLC. UA-type OPCs are used as protocol aligners. One computer is connected to the PLC, which also acts as an OPC UA server. Data from the OPC UA server can be accessed by other computers through a wireless network, and this computer acts as an OPC UA client. Figure 5 shows the system architecture design along with the connection flow. The software used is RSLink and RSLogix 5000 for PLC configuration and PLC programming, respectively. The KepServer software is the OPC UA for protocol alignment, the design of the HMI uses the Wonderware InTouch software and the simulation control using the Simulink feature in MATLAB.

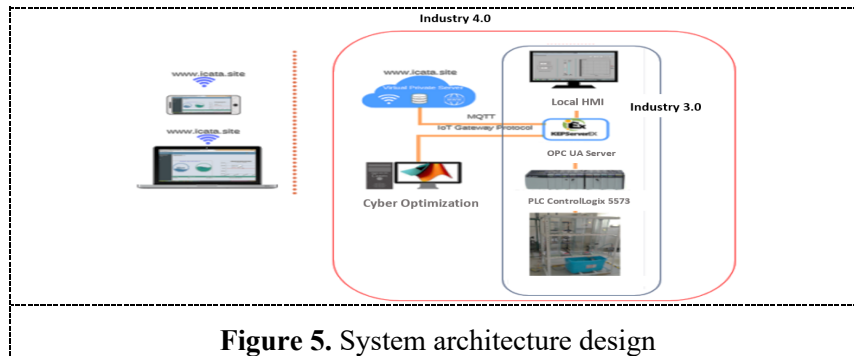


Figure 5. System architecture design

The three interacting tank system is simulated with MATLAB to determine the control parameters that can be applied to the physical system. Level data from the third tank contained on the OPC is sent to MATLAB with the OPC Toolbox on the Simulink feature in real-time. The third tank level data is used as feedback from the control system. Thus, the operator gets the controller parameter reference from the simulation before applying it to the actual three interacting tank system. The condition of the plant is displayed and can be set on the HMI. Data from the OPC server is sent to the cloud server using the MQTT protocol provided by OPC UA on the IoT gateway feature. The characteristics of the three tanks CPS system controller interact are as follows:

- The physical and cyber systems are modeled independently, and the cyber system is three interacting tank model in linear system but coupled through feedback control.
- Operation of the physical system is monitored in the cyber controller to provide the proper integral time of the physical system controller.
- Using LQR techniques, we design four integral time of PID controllers for the physical system over the control task. (Note that this is different from real-time systems task scheduling, but somewhat controller gains are designated at a defined condition for the system linearized over different operating points.)
- The PID controller in the cyber system uses LQR method to find the appropriate weighting matrices Q and R that minimize the cost function (13) for each operating interval for the PID controller in the physical plant.
- The performance of the PID controller in the physical plant is measured using the integral squared error (ISE) between the set point and the level of the third tank.

$$ISE = \int_0^t (e(t))^2 dt \quad ; \quad e(t) = SP(t) - LV(t) \quad (14)$$

3.2. Monitoring system via website

The cloud server system used in this paper functions to receive and store data sent via the MQTT (broker) data communication protocol that is stored and displayed via a particular Web address. Cloud server is built in the form of a virtual private server (VPS) computer. The VPS utilizes Google's service, the Google Cloud Platform. The hardware used for VPS purposes consists of Intel Broadwell as a CPU with 1.7 GB of RAM and 50 GB of storage capacity. The data center of the VPS is in the Asia-Southeast1-b zone, Singapore. The software used for the basic needs of the server is an operating system in the form of Linux, MySQL which functions as a place to store data, PHP which functions as a website developer, and Apache which is used to serve the Web/www facilities using HTTP protocol.

Four data are received by the broker from OPC UA as the sender of data, namely, third tank level (LV), set point given to the third tank, percentage of valve control opening (CV), and time stamp when OPC UA sends data to the broker. Data are sent to brokers with specific topics. The topic used for this system is "iotgateway" in a JSON format to regulate packet formation so that there are multiple IDs in

one same data package. After the JSON data packet is received by the subscriber, the data packet is broken down according to their respective ID. The limitations of the problem in this investigation are as follows:

- Application of CPS for the level of the three interacting tank system operating in the level range of 35–50 cm.
- Monitoring and controlling the level with DP transmitter used as controller feedback and interaction through the website.
- The protocol used for the Industrial IoT is the MQTT protocol.

4. Results and analysis

4.1. Mathematical model of system level three-tank interacts

The nonlinear dynamics of the three interacting tank system is linearized and divided into four interval areas based on the level of the third tank, namely, 0–15 cm, 16–30 cm, 31–45, cm and 45–70 cm. In the state space modeling of this system, only the matrix A changes based on operating point, while the values of matrix B , C , and D remain constant. Table 1 lists the mathematical model of state space with operating points in the level range above.

Table 1. A matrix value of the three interacting tank system of state space model

0–15 cm			16–30 cm			
$A = \begin{bmatrix} -0.3343 & 0.3343 & 0 \\ 0.3343 & -0.6686 & 0.3343 \\ 0 & 0.3343 & -0.3753 \end{bmatrix}$	$A = \begin{bmatrix} -0.2119 & 0.2119 & 0 \\ 0.2119 & -0.4238 & 0.2119 \\ 0 & 0.2119 & -0.2442 \end{bmatrix}$	$B = \begin{bmatrix} 0.0051 \\ 0 \\ 0 \end{bmatrix}$				
31–45 cm			45–70 cm			$C = [0 \quad 0 \quad 1]$
$A = \begin{bmatrix} -0.1767 & 0.1767 & 0 \\ 0.1767 & -0.3534 & 0.1767 \\ 0 & 0.1767 & -0.2022 \end{bmatrix}$	$A = \begin{bmatrix} -0.1767 & 0.1767 & 0 \\ 0.1767 & -0.3534 & 0.1767 \\ 0 & 0.1767 & -0.2022 \end{bmatrix}$	$D = [0]$				

The simulation is done using Simulink MATLAB R2015a software utilizing the S-Function block such that the state space equation can be defined in accordance with a predetermined area. PID control for simulations is performed on the PLC and transfer of control variable data and process variables between Simulink and PLC using OPC UA. Model validation is done by taking LV data in parallel between real plants and simulations and by comparing the two results using the RSQ function in Microsoft Excel software shown in table 2. RSQ is a function that calculates the square of the Pearson product-moment correlation coefficient of two sets of values, e.g., “x” and “y.” The R-squared value interprets the ratio of the variance “y” to the variance of “x.” If the R-squared results are close to 1, then the plot results of the simulation level graph are close to the level graph in the real plant.

Table 2. R-squared values from plot simulation chart and real plant

Condition	R-squared	Condition	R-squared
Valve opening 30%	0.987461	Valve opening 70%	0.995574
Valve opening 50%	0.996900	Valve opening 100%	0.996490

Table 2 shows that the R-squared value of the model is close to 1. Thus, it can be concluded that the three-tank system model provides suitable representation of the real plant system. Comparison of simulation graph results with water levels in real plants using the PID controller also confirms the model used because it produces an R-squared value between the two graphs of 0.9959.

4.2. PID tuning process

The initial tuning process of PID parameters is carried out by the LQR method in a trial error by changing the weights matrix Q and R , according to the division of the simulation modeling area.

Table 3 summarizes the PID parameter values for each level range utilized for the PID scheduling in the PLC ladder program.

Table 3. PID parameters for each water level range in tank 3

Level range	K_p	K_i	K_D
0–14 cm	15.1	3.68	11.4
15–29 cm	21	3.2	25.2
30–44 cm	24.7	3.06	35.8
45–60 cm	29.7	2.92	53.5

In optimizing the controlled level response, several simulations are performed using the selected K_i value using simple direct search method with steps half as long [24]. The K_i value obtained from tuning with LQR is denoted as K_{i0} , while the next K_i value is taken which is the minimum value of the integral gain on the PID controller. The next K_i is then chosen among the previous K_i values. Checking the K_i value is carried out continuously until the ISE results of the response of the water level in the simulation are smaller than the previous ISE. The optimization process is done by repeating the simulation to get the best ISE value, as shown in table 4. The K_i parameter is then implemented to the plant PID controller. Testing the results of optimization of the control before and after only displayed at the level of 10 cm, 25 cm, 40 cm, and 50 cm, as shown in figure 6. Figure 7 shows the results of calculating the ISE value of the level response before and after optimization.

Table 4. ISE simulation value in the set point from 10 cm to 50 cm

Level	K_i	ISE
10 cm	0.23	20.81
25 cm	0.8	12.79
40 cm	0.765	5.21
50 m	1.46	7.36

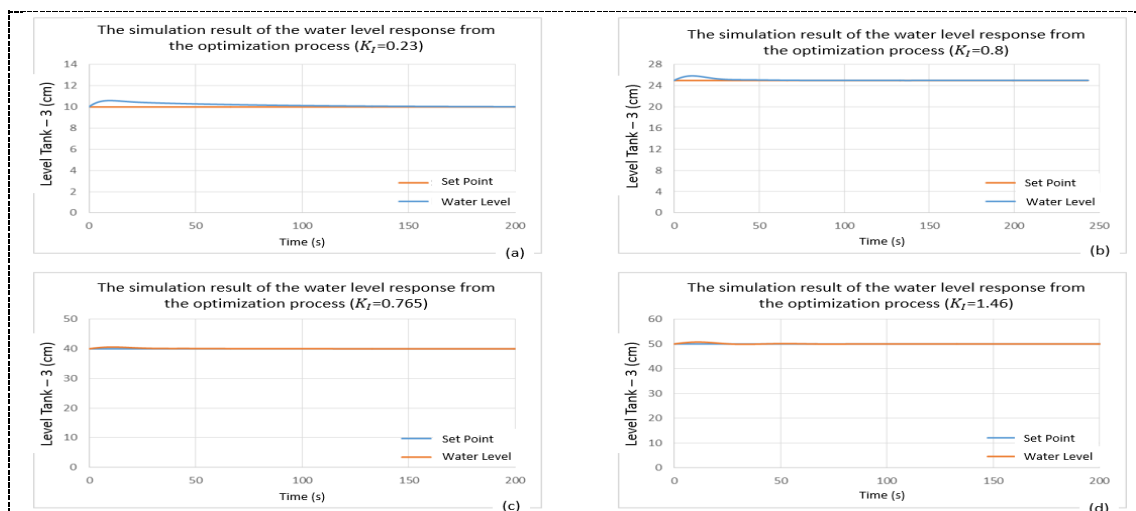


Figure 6. Simulation results using optimized K_i at different setpoints (a) 10 cm, (b) 25 cm, (c) 40 cm, and (d) 50 cm

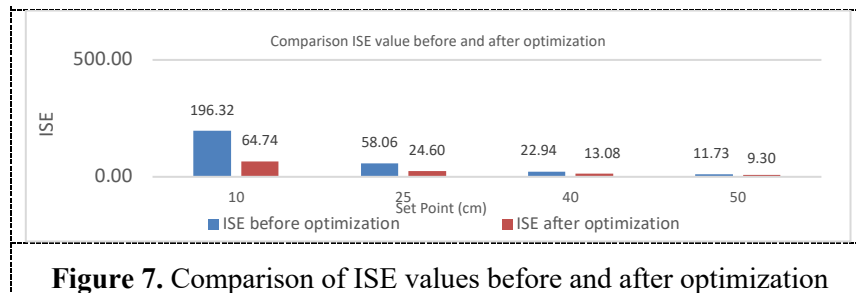


Figure 7. Comparison of ISE values before and after optimization

4.3. CPS implementation

CPS connects computing on a computer with a real plant, in this case monitoring the ISE value on a real plant. ISE value exceeding a predetermined limit will trigger a simulation to optimize. Optimization is done using a system modeling simulation that is calculated using Simulink software. Simulink and PLC communicate directly using OPC UA so that the results of the optimization can be directly applied to real plants. Figure 8 shows a Simulink block diagram used for optimization. The flowchart of the optimization algorithm can be seen in algorithm 1.

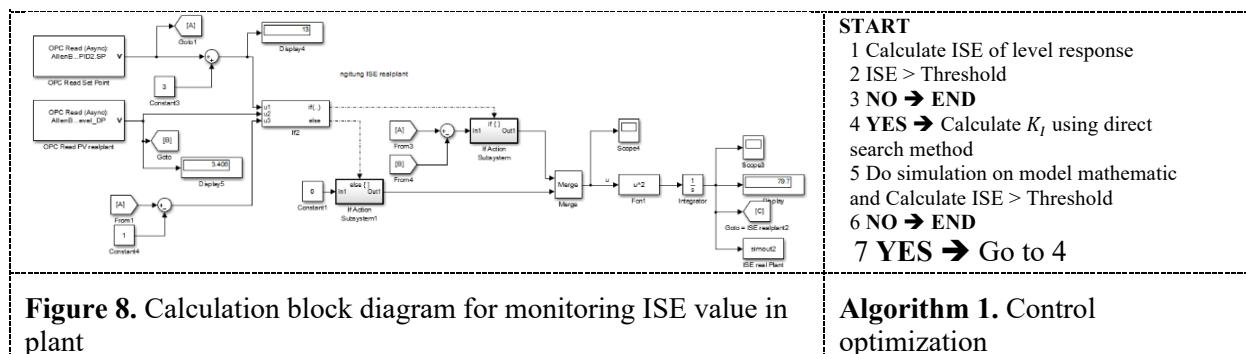


Figure 8. Calculation block diagram for monitoring ISE value in plant

Algorithm 1. Control optimization

Defining the maximum allowable ISE value based on the results of previous experiments, the system response at the set point of 40 cm is sufficient to represent a good level response. The experiment produced an ISE value of 22.94; therefore, the maximum allowed ISE threshold of 25 was chosen, as shown in figure 8. Optimization was carried out along with the operation of the plant. After getting the optimal K_I value that minimizes ISE value, the K_I parameter is then implemented to the plant PID controller. The graphs below compare before and after control optimization using CPS.

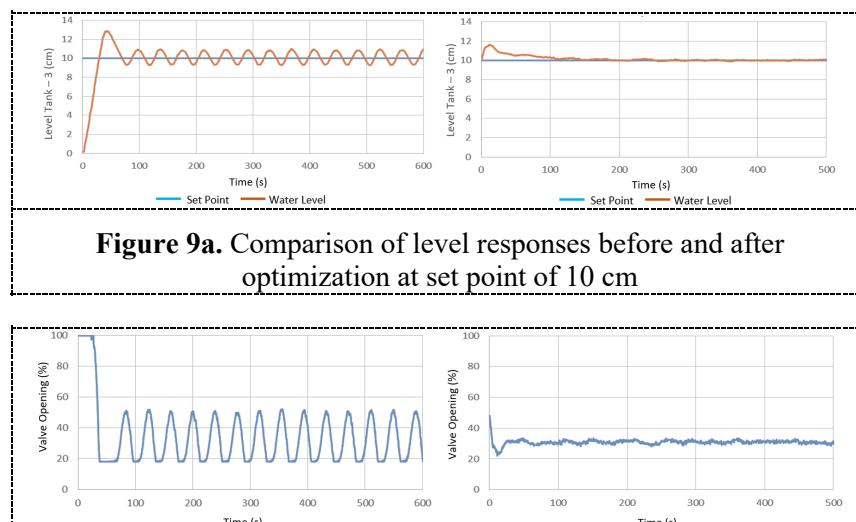


Figure 9b. Comparison of valve openings before and after optimization at set point of 10 cm

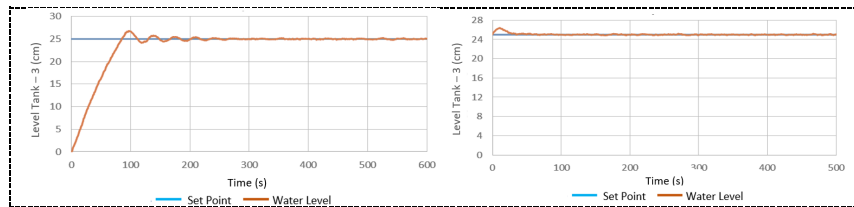


Figure 10a. Comparison of level responses before and after optimization at set point of 25 cm

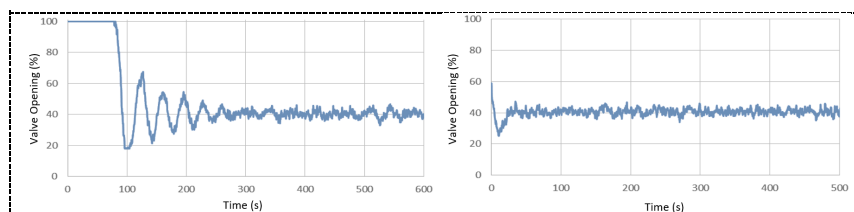


Figure 10b. Comparison of valve openings before and after optimization at set point of 25 cm

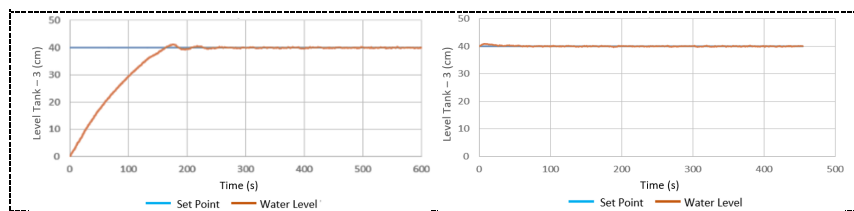


Figure 11a. Comparison of level responses before and after optimization at set point of 40 cm

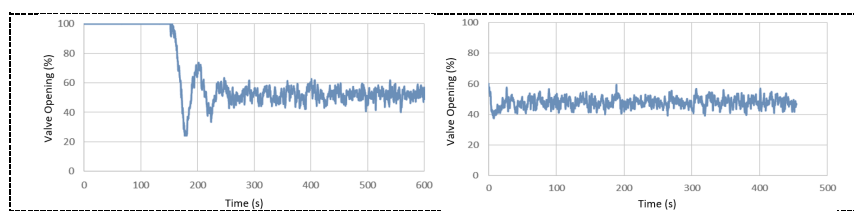


Figure 11b. Comparison of valve openings before and after optimization at set point of 40 cm

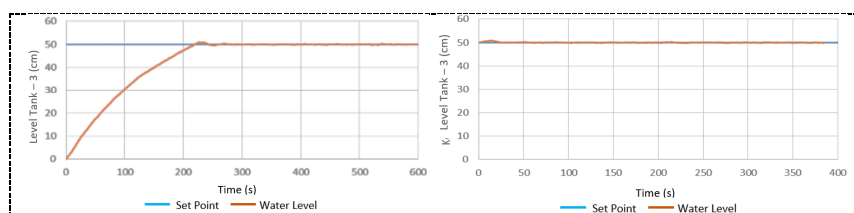
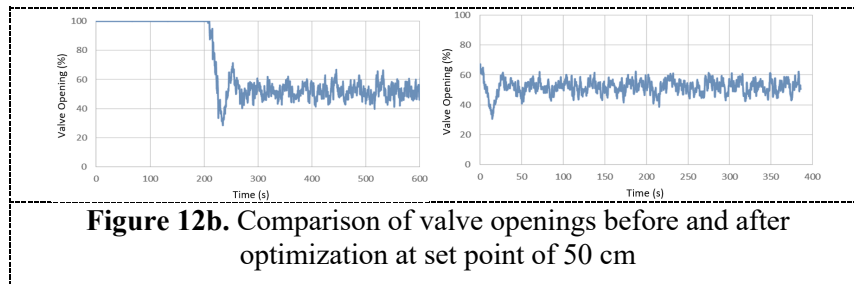
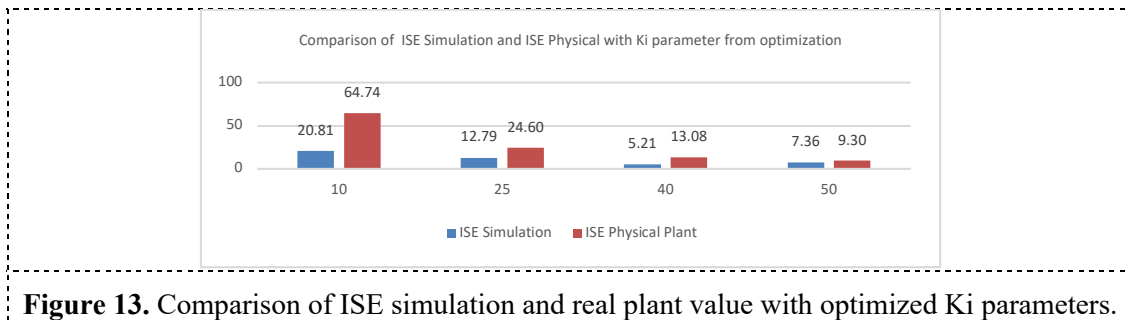


Figure 12a. Comparison of level responses before and after optimization at set point of 50 cm

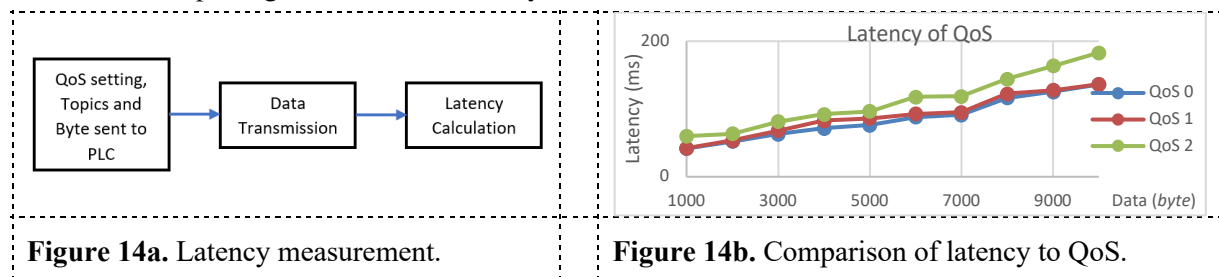


Figures 9–12 show the output response and the control input of the three-tank systems. Figure 13 is a comparison of ISE values between simulation results and their implementation in real plants. This happens because the valve opening in the real plant takes a range of 5 s to open from 0% to 100%, so that when the PID output signal gives a valve opening value, then there is a delay from the control valve to reach the opening value. Whereas in the simulation there is no delay, the ISE value obtained is smaller when compared to the real plant ISE value because the valve opening value is more accurate.



4.4. QoS Performance

Figure 14a illustrates the procedure used to look for the latency value [25] of QoS 0, 1, and 2. Data transmission uses the `iotgateway` feature on OPC UA with the amount of data sent fixed. Sending data via the MQTT protocol with variations in QoS is 0, 1, and 2 [26] with large data sent in sizes of 1000–10,000 bytes with a variation of data every 1000 bytes. Data are sent with an Internet connection with download and upload speeds of 36.38 Mbps and 39.39 Mbps. Based on the standards issued by the Telecommunications and Internet Protocol Harmonization Over Networks (TIPHON) [27], the trial results have a latency value that is included in the very good category because the latency is less than 1500 ms in sending 1000 bytes data, as shown in figure 14b. Hence, it can be said that the data transmission takes place in real-time. From the results of missing data measurements, QoS 0.1 or 2 can send 1000 data packages with 100% delivery rate, and no data is lost.



5. Conclusion

This paper presented the development of CPS for industrial process automation that still uses the programmable logic controller (PLC). The used process system was the three interacting tank process controlled by the standard PID controller using the LQR method for tuning to provide a guaranteed

stability of the closed-loop system. A cyber system functioned to select the integral time parameter of the PID controller when the ISE of the controlled cyber-physical part exceeded a specified condition boundary. The CPS successfully assisted the PID controller to result in smaller ISE. The experimental results showed that OPC UA was able to work as a horizontal and vertical integrator well so that communication in CPS still met the real-time criteria with data delivery rate of 100%. CPS was able to provide better control performance compared to only using PLCs with significant ISE improvements.

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