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ICT-Architecture design for a Remote Laboratory of Industrial Coupled Tanks System

Ferlando Mkiva[a,b], Nico Bacher[a,b], Jens Krause[a,b], Theo van Niekerk[a], John Fernandes[a], Antonio Notholt *[b]

[a] *Nelson Mandela University,University Way, Port Elizabeth 6019, South Africa*
[b] *Reutlingen University, Alteburgstraße 150, Reutlingen 72767, Germany*

Abstract

Different network architectures are being used to build remote laboratories. Historically, it has been difficult to integrate industrial control systems with higher level IT systems like enterprise resource planning (ERP), manufacturing execution systems (MES), and manufacturing operations management (MOM). Getting these systems to communicate with one another has proven to be relatively difficult due to the absence of shared protocols between them. The Open Platform Communications United Architecture (OPC-UA) protocol was introduced as a remedy for this issue and is gaining popularity, but what if open-source protocols that are widely used in the IT industry could be used instead? This paper presents the development of an IT-Architecture for a cyber-physical industrial control systems laboratory that enables a seamless interconnection and integration of its elements. The architecture utilises Node-Red technology. Node-RED is an open-source programming platform developed by IBM that is focused on making it simple to link physical components, APIs, and web services. This cyber-physical laboratory is for learning principles of an industrial cascaded process control factory. Finally, this text will also discuss future work relating to digital twin (DT). A coupled tank system is selected as a teaching factory to illustrate a range of fluid control application in a typical chemical process factory.

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Keywords: Node-Red; Coupled Tank System; Process Control; S7-1500; Cyber-physical Laboratories; Learning Factory; Digital Twin (DT)

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1. Introduction

The use of remote laboratories towards in the field of control engineering is not new; In the last two decades, remote laboratories have been used with success in the field of automatic control, and their development in this area changes in response to the technologies that are available for industrial control [8]. Reutlingen University from Germany and National Technical University Dnipro Polytechnic from Ukraine are also in a joint project called Laboratories Across Borders (LAB) which is a research on development of cyber-physical laboratories. The technological architecture that underpins the educational remote laboratories must take into account the most recent developments in digitalization [5], especially when those developments rely on physical systems of an industrial scale. Hence the basis of the Fourth Industrial Revolution and the Industrial Internet of Things (IIoT) must be considered. The basis of these two concepts put great emphasis on interconnectivity, cybersecurity, cloud and edge computing [1] [7] [3] [11].

Correspondingly, an IT-Architecture for a cyber-physical industrial control systems laboratory that makes it easier to connect and integrate its components is presented in this paper. It is primarily centered on a single technology, Node-RED, which offers benefits including a simple yet configurable user interface for consumers.

Node-RED is an open-source programming platform developed by IBM that is focused on making it simple to link physical components, APIs, and web services. As programming is done graphically utilizing flows in the web browser, where the interface editor is generated, applications may be created quickly. The most recent edge computing devices from some of the biggest industrial equipment producers, including Siemens which is the producer of main controller of the apparatus used in this research support the Node-RED technology [4].

When running the experiments, the student only interacts with the frontend but has access to all functionalities. The majority of data transport interfaces are predefined: The PLC is connected to every sensor and actuator technology available. A computer that is connected to the network is connected to the PLC. The Siemens S7 PLC essentially provides the option of hosting the web server directly on the PLC, for which all required papers must be uploaded to the PLC. Hosting the web server on a different computer in the lab is an extra choice that this paper will use and will be discussed in detail in section 3 on page 4.

2. Background

The use of Water Tank System is popular in industrial applications especially for the chemical process systems. ”The liquid level and flow control in Coupled Tank System are classical benchmark control problem” [9, p. 667]; and because of its characteristics, the coupled tank system has attracted attention of many researchers in the literature for the last two decades [2]. The Coupled tank system can be Single-Input Single-Output (SISO), where liquid is pumped to one tank and the second tank is supplied by the first tank. These systems can also be Multi-Input Multi-Output (MIMO). The process industry requires liquids to be pumped, stored in tanks and transported to the next location in a systematic manner that can be easily controlled and monitored. The centre of interest in each process is the control of liquid level. With the knowledge that “chemical engineering systems are also at the heart of our economies” [10, p. 1] one can understand the importance of a thorough understanding of these basics. The coupled-tank tank level control system is ideal for real life control implementation on a smaller scale.

2.1. Coupled Tank System Apparatus

Coupled Tanks Apparatus shown in figure 1 on the next page relates specifically to fluid transport and liquid level control problems as they would typically occur in process control industries. It may also, however, be used as a practical introduction to the design, operation and application of control systems in general.

The Coupled Tank Apparatus comprises two separate vertical tanks, which are connected by a flow channel. A ball valve may be used to vary the cross-sectional area of the channel and, hence, change the flow characteristics between the tanks. The degree of the valve/flow varieties possible offers a wide scope of actual alternatives and flow characteristics to be overcome by the controller.

The Are two pumps positioned at the back, the pumps are used to fill the tanks with liquid at varied rates. The control panel door consist of two potentiometers that are used to set a desired height in the tanks, then the speed of the pump is adjusted by the PLC to fill the left-hand tank, to a required level, and the system performance may be monitored. Alternatively, the right-hand tank may be filled from the head of water contained in the left-hand tank via the variable valve opening and again the performance characteristics determined.

Each tank is fitted with an inverse frequency shift capacitance continuous liquid level transducer. This device is equipped with active-shield technology so measurement is unaffected by material build-up in active shield section. The actual transducer element uses a 2-wire HART protocol (4 to 20 mA) current loop design.

A separate tank in the base of the mechanical structure acts as a water reservoir for the apparatus. For protection of the pumps, a point level sensor is installed to alert the user and to interlock so that the pumps do not start when the reservoir is empty.

The output from the pump is sensed by an in-line flow transducer of magnetic type. The flow measuring principle is based on Faraday’s law of electromagnetic induction. Magnet coils mounted diametrically on the measuring pipe generate a pulsed electromagnetic field. The liquid flowing through this electromagnetic field induces a voltage.

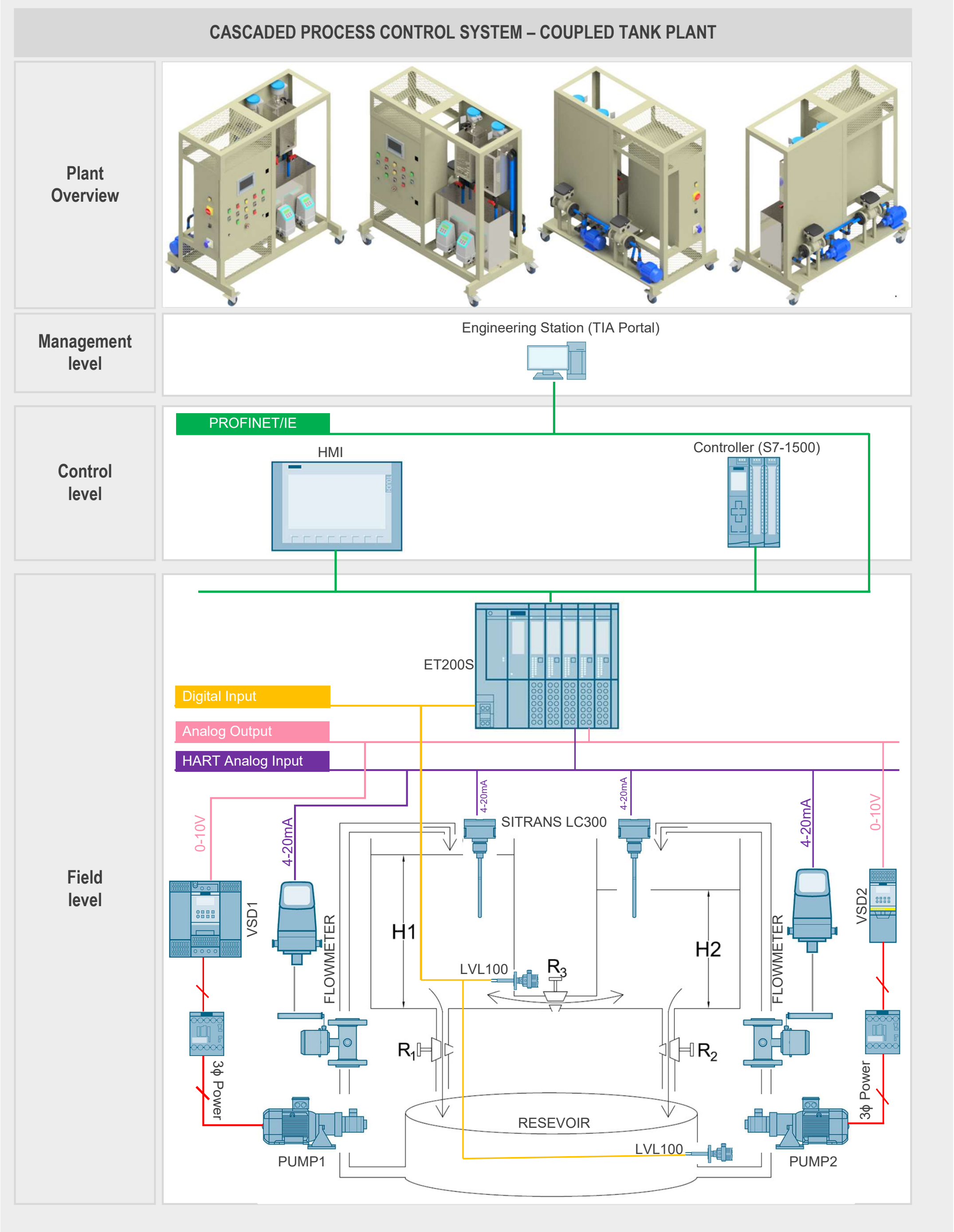


Fig. 1. Coupled Tank Hardware Communication Diagram.

3. Proposed Architecture

Figure 2 presents a proposed Full-Stack Remote access architecture that will be developed in this research project. This architecture comprises three different elements: The far left of the diagram starts with the front-end, where the user (student) accesses a predefined dashboard from moodle site or from a web browser. The user initially accesses the main website which has theoretical information for the experiments and details about the experimental setup, this website will be accessed by anyone as it only provides knowledge. The back-end starts from the third block after the firewall, this will be a web server hosted in Nelson Mandela University (NMU) server. This server will host the Main website, the databases and node-red application. On the other side of this server there is a Desktop computer next to the physical system, this PC runs TIA portal and communicates to the PLC.

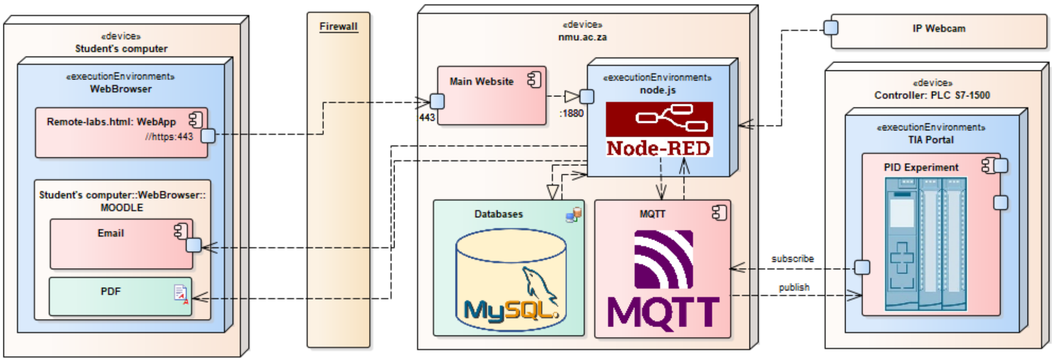


Fig. 2. Proposed System Architecture

3.1. *Added value of the current work and evaluation method for knowledge retention*

The combination of technologies used in this proposed architecture is not new, Domínguez et al [4] successfully utilized a combination of node-red and PLC to develop a remote laboratory, which serves as the foundation for the proposed architecture in this project. The goal of this architecture is to automate the management of laboratory sessions, enabling users to book practical sessions on the platform and receive a login token. With this system, users can access the platform anytime without the need for an instructor to manually select who can use the system. Additionally, the booking management system will be secure and limited to registered students only, ensuring the safety and integrity of the platform.

The aim of practical experiments is to enhance the theorems and knowledge that the students learn in the theoretical part of their studies. The remote experimental platform that is developed in this research will be equipped with an evaluation method for knowledge retention. It will be discussed in section 3.3 on the next page that the system must allow the students to generate a pdf report at the end of a practical section, the report will have sections that require discussion of results from a student accompanied by a predetermined quiz questions that will form part of the report.

The designed architecture will also integrate the Moodle learning site to the platform to automate the submission of the generated practical report. This feature will assure that the report is not altered by the students.

Overall, the proposed architecture has the potential to offer an efficient and secure solution for managing laboratory sessions, enabling greater access and flexibility for students while minimizing administrative workload for instructors.

3.2. *Web-cam Integration*

This section discusses the integration of the web-cam to the experiment UI. The aim of having a web-cam to the platform is to allow the users to monitor the response and status of the plant variables in real time using the video feed. Moreover, the live-stream serves as an additional safety measure in case of any unforeseen events that may occur with the system or in the university lab. If there is something that cannot be conveyed through the web-page, the student can observe it on the live-stream and take necessary action, including pressing the emergency stop button if required.

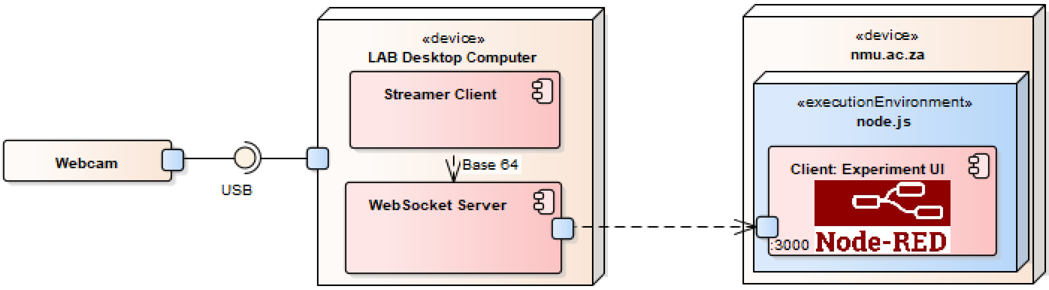


Fig. 3. Data Flow from Web-cam to client

Figure 3 depicts the basic architecture and data flow for the video feed from the web-cam to the node-red experiment UI.

3.3. *Experimental Report Generation*

Users will be able to save the data from the PLC in the form of a PDF file as a report or as a simple CSV file in addition to controlling and displaying it. The node-red-contrib-pdfmake is utilized for this purpose. According to the Javascript library PDFmake's documentation, PDF files can be generated with this node. Figure 4 shows the flow used for creating the report.

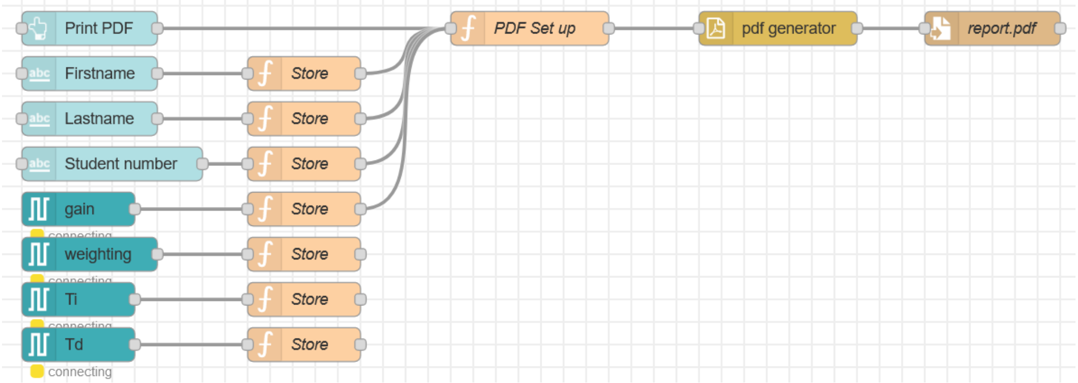
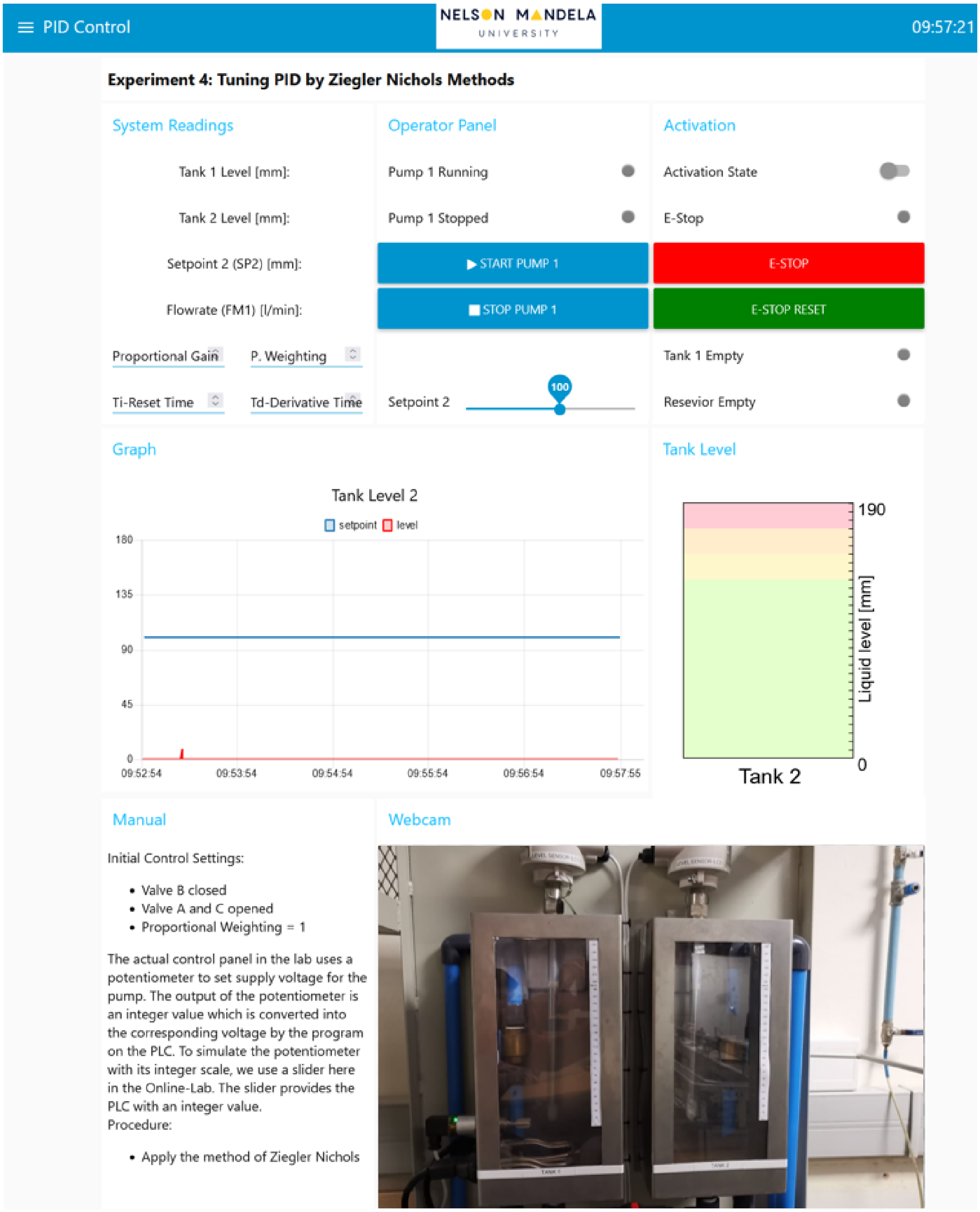


Fig. 4. Flow for PDF Generation

Clicking the Print PDF button creates a PDF file according to the Set Up PDF function. As input for this function the data of the user and experimentally determined PID parameters are used. These values are stored in the Store function as global variables, so that with a button click the values of all variables are also available. Later, a MySQL database will be used to store the data of the experiment.

3.4. User Dashboard

The dashboard that customers will see is shown in figure 5. It has elements that are frequently found in user interfaces of remote laboratories, like a video stream and a line chart of the pertinent variables. The students can have a better grasp of the system and the impact that changes in the PID parameters have on its behaviour by keeping track of the status of plant variables using the chart or the video feed.



Initial Control Settings:

- Valve B closed
- Valve A and C opened
- Proportional Weighting = 1

The actual control panel in the lab uses a potentiometer to set supply voltage for the pump. The output of the potentiometer is an integer value which is converted into the corresponding voltage by the program on the PLC. To simulate the potentiometer with its integer scale, we use a slider here in the Online-Lab. The slider provides the PLC with an integer value.
Procedure:

- Apply the method of Ziegler Nichols

Fig. 5. Predefined Dashboard

4. Practical Educational Experience

4.1. SISO PID Level Control by Ziegler Nichols

It is important for students to understand that in an industrial factory, sometimes it might be not possible to determine the transfer function of the plant in order to tune the controller, but there are practical theorems that can be used to tune the parameters of the controller without knowing the transfer function. In this section, PID parameters will calculated using Ziegler-Nichols method. Figure 6 shows the block diagram the system with the PID controller. In this diagram, the PID in the PLC is scaling the actuating signal sent to the drive, and the drive start the pump with a corresponding speed. The level of tank 2 is the output in this diagram. This is only using one pump 1.

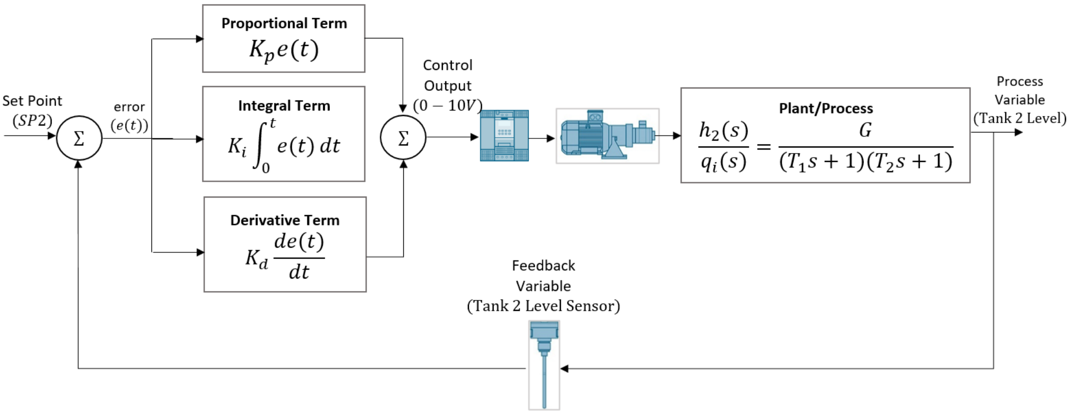


Fig. 6. SISO Closed Loop System With PID Controller

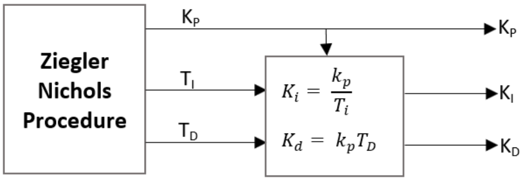


Fig. 7. Ziegler-Nichols Tuning Procedure

Figure 7 shows the procedure for Ziegler-Nichols. The goal here is to choose K_p, K_i, K_d appropriately.

- initially, a small gain ok k_p is used
- k_p is increased until neutral stability
- Ultimate gain is recorded $k_u = k_p$ at neutral stability
- Then a Ziegler-Nichols look up table is used.

Figure 8 on the next page shows the response when a gain of 3.4 is used. k_p only is used in this case. The level in tank 2 is oscillating and the period of this oscillation is recorded.

Figure 9 on the following page shows the response when a PI controller is used with $k_p = 3.4$ and $T_i = 18.45s$, the system reaches the set-point, but it takes time to settle. In figure 10 on the next page, the PID controller introduced the derivative term, and it can be seen that the response is fast and acceptable. The value of the derivative term used is $T_d = 4.67s$.

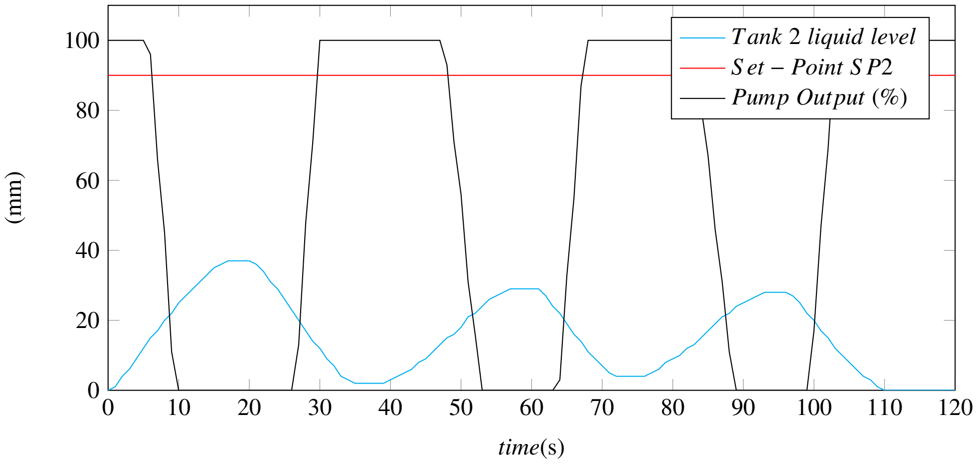


Fig. 8. Proportional Term Effect

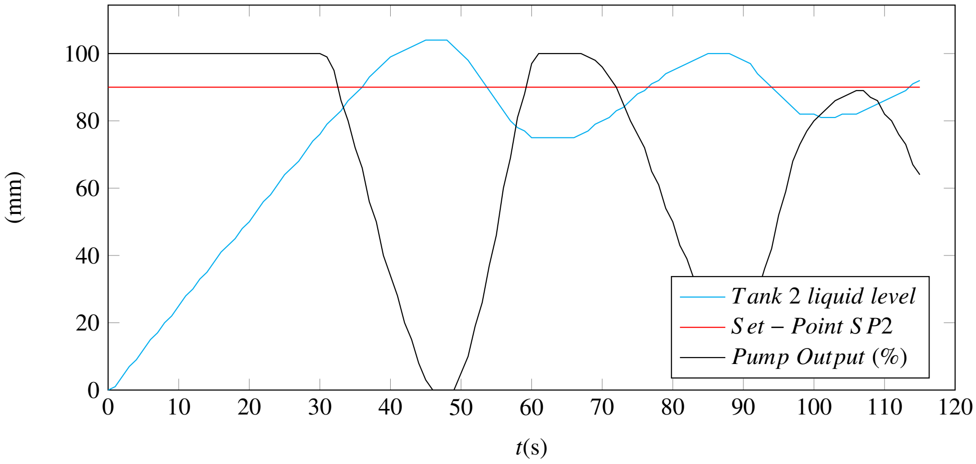


Fig. 9. Proportional and Integral Term Effect

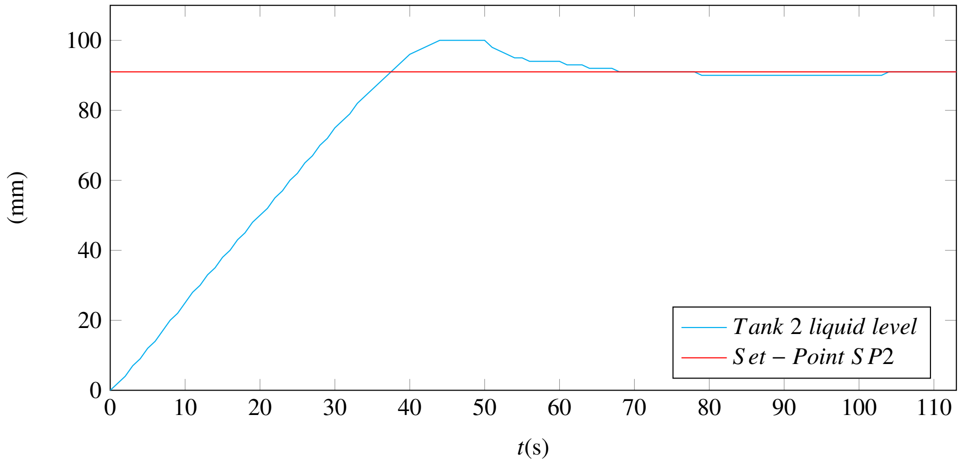


Fig. 10. Water level (heights)

5. Conclusion and future outlook

This work presented a comprehensive solution for remote laboratory architecture using Node-RED and Web-Socket proxy server. The article explained how these subsystems can be interconnected seamlessly to provide a smooth experience for the user. In addition, the paper highlighted a secure and efficient method for managing laboratory sessions that promotes flexibility for students and reduces the administrative workload for instructors. To evaluate the effectiveness of the platform, the article proposed a method that links the designed platform to a Moodle learning site for knowledge retention evaluation. To illustrate the practicality of this strategy, the paper showcased how students can set up a PID controller on a level control loop of an experimental facility accessible to them at Nelson Mandela University. Overall, this work demonstrates the potential of remote laboratory architecture to provide students with valuable hands-on experience in a secure and efficient manner.

Application of open-source technologies like Node-RED are suitable to enable data exchange with industrial hardware in educational settings. Moreover, the utilization of standard protocols like web-socket-server would facilitate the development of educational tools that enable the remote operation of this kind of physical systems.

5.1. Future outlook

Papacharalampopoulos et al [12] research suggests the use of digital twins (DTs) that expand the idea of process control to include optimizing multiple performance indicators. This is accomplished by utilizing data-based models to establish the mathematical connections between process parameters and performance indicators (KPIs). Another successful study by He et at [6] suggested a method for estimating the fluctuating flow state of a pumping station using a digital twin approach. These two solutions could be used in future works where students would use a digital model of the coupled tanks apparatus to compare with the results obtained from the physical system and also be able feed data back to the physical system for performance optimization. The mathematical link in this case could utilise technologies like SIMIT.

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