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Development of a human machine interface based learning system for pump performance practicum

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ABSTRACT

The digitalization of physical fluid phenomena in pump performance teaching media remains a significant challenge in the development of online and laboratory-based learning tools. This study aims to develop a Human Machine Interface (HMI) based device as a teaching aid to support pump performance practicum for students. The system is designed to provide informative, real time, and responsive visualizations associated with valve opening adjustments and motor shaft rotation. The development process follows the waterfall model, which includes requirement analysis, system design, implementation, and verification. The resulting HMI interface dashboard demonstrates interactive capabilities, enabling users to monitor and control system parameters effectively. The system responds dynamically to operational changes and displays variations in key parameters such as pressure and fluid flow rate in real time. The implementation of this HMI based learning media is expected to enhance students' understanding of fundamental pump performance concepts by providing a more engaging and intuitive learning experience. Through dynamic visualization and interactive control features, the system bridges the gap between theoretical knowledge and practical application during laboratory sessions.

1. Introduction

In industrial practice and engineering education, a comprehensive understanding of pump systems is essential to enhance operational efficiency and data accuracy. One commonly employed approach in teaching pump systems involves the use of instructional media in the form of a pump performance testing setup, which consists of several key components, including a centrifugal pump, piping system, vacuum gauge, pressure gauge, flow meter, ammeter, and voltmeter. This setup utilizes a water centrifugal pump, which is widely applied in hydraulic systems within the field of mechanical engineering. However, the current operation of this installation is still conducted manually, which may lead to less accurate data acquisition and reduced efficiency in data recording.

Efforts in engineering education are currently undergoing a shift from conventional methods that rely on hands on facilities toward virtual based learning approaches. Numerous studies have demonstrated that virtual based learning can yield outcomes comparable to, or even better than, traditional methods in both cognitive and affective domains [1], [2]. Seifan et al. [3] reported that the use of virtual laboratory environments enhances students' laboratory skills as well as their non cognitive attributes. Furthermore, blended learning, which combines online and offline instruction, has been proven effective in improving academic performance [4].

Fig. 1. Pump Installation with a Manual Control System

The implementation of Augmented Reality (AR) has also made a significant contribution to improving efficiency in engineering education. Lai et al. [5] developed AR based training media for welding education, demonstrating reductions in operational costs and material waste. Similarly, Agrawal and Pillai [6] integrated AR technology into vocational training, resulting in significant improvements in technical competencies.

In industrial applications, Programmable Logic Controller (PLC) technology has been widely adopted due to its flexibility, robustness in harsh environments, and ease of integration with various systems [7], [8]. PLCs are used to process input signals into automated control commands for actuators, sensors, motors, and other components, thereby enabling efficient and precise system operation. The integration of PLC with Human Machine Interface (HMI) provides an interactive visual interface that facilitates monitoring and control processes [9].

The use of virtual based media for monitoring industrial system performance continues to evolve. McDonald and Zmeureanu [10] developed a Virtual Flow Meter (VFM) to monitor flow in cooling systems, while Andiroglu et al. [11] and Wang et al. [12] proposed VFM methods based on motor power consumption measurements to evaluate pump performance. Liu et al. [13] utilized parameter-based models to monitor pump performance in HVAC systems to enhance energy efficiency. Similar findings were reported by Cetasol [14], which employed virtual approaches to monitor fuel consumption and the performance of marine pump systems.

In addition to industrial technology advancements, several educational institutions and technical training providers have begun integrating PLC and HMI learning into their curricula through online and hybrid formats [15]. This trend reflects an urgent need to provide instructional media aligned with the development of Industry 4.0.

Based on observations of existing pump testing systems, it was found that manual methods for controlling and recording operational parameters present several limitations. Therefore, this study focuses on the development of a PLC based control system integrated with an HMI. The implementation of the HMI is expected to provide informative and interactive visualizations related to valve opening adjustments and pump motor shaft rotation.

The integration of teaching aids or interactive learning tools in engineering education has gained increasing attention due to their ability to enhance student engagement, improve learning outcomes, and overcome the limitations of conventional teaching methods [16], [17]. Although numerous studies have explored the application of virtual systems in both educational and industrial contexts, this research offers a novel contribution by developing a teaching aid-based system utilizing PLC control integrated with HMI for pump performance testing. Unlike manual systems that require direct parameter adjustments by users, and purely virtual simulations that do not fully represent the physical dynamics of fluid flow, the system developed in this study enables automated operation and monitoring. This approach provides a practical learning experience that more closely resembles real industrial conditions, thereby enhancing students' competencies in understanding modern pump control systems. It is expected that the developed instructional media will serve as an effective solution for improving the quality of engineering education in alignment with ongoing industrial technological advancements.

2. Method

The development of the PLC and HMI based teaching aid for pump performance testing in this study follows the Waterfall method, which consists of requirement analysis, system design, implementation, and verification stages. According to Roger S. Pressman [18], the Waterfall model is a classical software development approach characterized by a systematic and sequential process. To bridge engineering and educational aspects, system development is grounded in a theoretical framework of instructional media that emphasizes the importance of interactive learning tools in enhancing student engagement, conceptual understanding, and practical skills. Accordingly, the system's technical functions are aligned with the objectives of applied engineering education.

The verification stage is conducted to ensure that the system operates in accordance with the design specifications, including the reliability of sensors in detecting flow condition variations, the stability of pump control via PLC, and the clarity of monitoring visualization on the HMI. Furthermore, the validation stage is associated with learning objectives through expert evaluation by lecturers in the fields of automation and engineering education to assess the suitability of the system as an instructional medium. Limited trials involving students are also conducted to evaluate usability, information readability, and the system's contribution to their understanding of pump performance and control systems.

Fig. 2. presents the development framework of the HMI integrated pump performance testing teaching aid system.

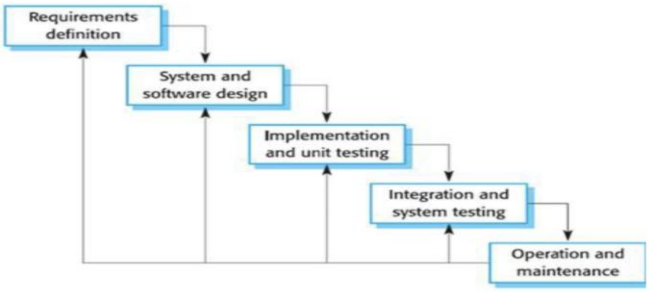

Fig. 2. Development stages of the HMI integrated pump performance testing teaching aid system.

2.1 System Requirements

Before commencing the design process, system requirements and functional specifications were defined to provide a structured reference and establish design constraints. This step ensures clarity in the development stages and outlines the limitations that must be addressed throughout the system implementation. The following requirements are proposed for the pump control system (Table 1).

The designed pump installation control system requires compatible hardware and software components that meet the specified system requirements. These requirements include the selection of appropriate PLC, HMI, sensors, actuators, and supporting software.

2.1.1 Hardware Components

a. PLC and HMI Components:
The selection of PLC and HMI components is tailored to the system requirements. The PLC used in this study is the Siemens S7-1200, equipped with one analog output module and one analog input module, configured according to the number and type of sensors. The HMI utilized is the Siemens KTP700.

b. Sensors and Actuators:
The selection of sensors is based on system requirements, with specifications aligned to the characteristics of the pump and the PLC used. This study employs several sensors and actuators. First, a proportional valve is used to regulate the fluid flow rate. Second, a solenoid valve functions to open and shut off the flow according to the pump operating principles. Third, a pressure sensor is used to measure fluid flow pressure. Fourth, a vacuum sensor is utilized to measure the suction pressure of the fluid flow. Fifth, a flow meter sensor is employed to determine the volumetric flow rate of the fluid.

In determining the appropriate sensors, it is necessary to consider the pressure, flow rate, and vacuum conditions within the pump system. The following presents the theoretical calculation process. The known parameters are as follows:

Total head of the pump = 27 m

Maximum head (h) = 27 m

Density of water (ρ) = 1000 kg/m^3

Gravitational acceleration (g) = 9.8 m/s^2

Pump capacity = 18 L/min

The sensor calculation process is described as follows:

a) Pressure Sensor

$$P = \rho\, g\, h \tag{1}$$

$P = 1000 \times 9.8 \times 27$

$P = 264600$ Pa $= 264.6$ kPa

b) Vacuum Sensor

1 atm = -76 cmHg

= - 101.325 kPa

c) Flow Meter Sensor

The minimum water flow capacity of the pump is 18 L/min, which is in accordance with the specifications of the selected flow meter sensor.

Table 1. System Requirements

No	Main Requirement	Description	Remarks
1	Sensors	The sensors used must be capable of measuring pressure, vacuum pressure, and water flow rate	- Pressure sensor - Vacuum sensor - Flow meter
2	Automatic Operation	The valve opening is automatically controlled, and the pump is operated via the HMI	- Proportional valve - Pump
3	Data Processing	The system processes parameters including flow rate, fluid velocity, and total head generated by the pump	- Calculation of total head - Calculation of flow rate and flow velocity
4	Data Visualization	Displays suction pressure, discharge pressure, and resulting water flow rate	The displayed data are obtained from measurements of pressure sensors, vacuum sensors, and the flow meter

Based on the above calculations, it can be concluded that the table below presents sensors with specifications that are consistent with the calculated requirements.

Table 2. Sensor Specifications and Operating Ranges

No.	Sensor Type	Sensor Model	Specification	Operating Range	Criteria	Quantity
1	Pressure Sensor	SMC PSE564	0 – 500 kPa	0 – 225.4 kPa	Meets Requirements	3
2	Vacuum Sensor	SMC PSE561	-101 – 0 kPa	-101 - 0 kPa	Meets Requirements	1
3	Flow Meter Sensor	SMC PF3W740	5 – 40 L/min	0 – 18 L/min	Meets Requirements	1

2.1.2 Software

The software used in this study is TIA Portal V16, which is the integrated development environment provided for the Siemens S7-1200. The selection of the PLC type is based on several considerations, including the power supply type, the number of input and output terminals, and the type of output circuitry.

2.2 System Design

The following figure presents the system block diagram for the design of the control system.

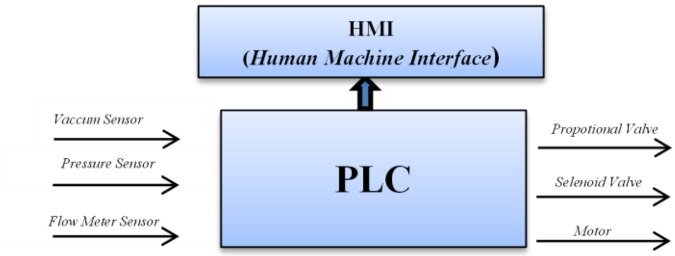

Fig. 3. System block diagram

Based on the system block diagram, it can be described that the inputs consist of a vacuum transducer, a pressure transducer, a flow meter transducer, and a PLC program in the form of signals that are processed to generate outputs in the form of valves and a motor. In addition, a Human Machine Interface (HMI) is incorporated to control and execute the PLC program in accordance with the designed operating principles.

The operating principle and configuration of the pump system are relatively simple and can be described as follows:

1. Single Pump Operation
   The single pump configuration utilizes one pump and three solenoid valves.
2. Series Pump Operation
   The series pump configuration employs two pumps and four solenoid valves.
3. Parallel Pump Operation
   The parallel pump configuration utilizes two pumps and five solenoid valves.

At this stage of waterfall method, the previously developed design concept is implemented. This phase involves the development of the control system program and the interface for the pump installation. Prior to programming, it is necessary to define the input and output configuration as well as the wiring diagram. The following outlines the sequence of processes carried out during the system design stage:

2.2.1 I/O List and Addressing

The table below summarizes the input/output (I/O) configuration used in the system programming.

Table 3. Input/Output (I/O) List

No	Component	Position	Address
1	Vacuum Sensor 1	Input	%IW112
2	Pressure Sensor 1	Input	%IW114
3	Pressure Sensor 2	Input	%IW116
4	Pressure Sensor 3	Input	%IW118
5	Flow Meter Sensor	Input	%IW64
6	Motor 1	Output	%Q0.0
7	Motor 2	Output	%Q0.1
8	Solenoid Valve 1	Output	%Q0.2
9	Solenoid Valve 2	Output	%Q0.3
10	Solenoid Valve 3	Output	%Q0.4
11	Solenoid Valve 4	Output	%Q0.5
12	Solenoid Valve 5	Output	%Q0.6
13	Solenoid Valve 6	Output	%Q0.7
14	Proportional Valve	Output	%QW96

a. Analog Input Module
   The analog input module is used to acquire and process signals from multiple sensors, including the pressure sensor, vacuum sensor, and flow meter. The measured data from these sensors are subsequently visualized through the Human Machine Interface (HMI).
b. Analog Output Module

In addition to the analog input module, an analog output module is utilized to generate analog signals from the control system. These output signals typically conform to standard industrial ranges, such as 4–20 mA or 1–10 V.

2.2.2 Wiring Diagram

A wiring diagram is a schematic representation that illustrates the electrical connections and cabling configuration of system components.

a. Power Wiring

The pump installation utilizes a single-phase pump operating at 220 V, consisting of line and neutral connections. The line supply is connected to a miniature circuit breaker (MCB), then routed through a relay, and subsequently supplied to the motor circuit.

b. Input Wiring

The input wiring consists of several components that serve as inputs to the control system, including:

1. Pressure sensor
2. Vacuum sensor
3. Flow meter sensor

c. Output Wiring

The output wiring consists of several components that function as outputs of the control system, including:

1. Proportional valve
2. Solenoid valve
3. Motor

2.2.3 PLC Programming

The development of the PLC and HMI programs was carried out using TIA Portal V16. The programming stages are described as follows:

a. Device Configuration in TIA Portal

The PLC hardware components were first configured in the TIA Portal environment by adding the required devices to the project.

b. Pump Operation

The pump operation is programmed based on three operating principles: single, series, and parallel configurations. These configurations involve two pumps and six valves that regulate the fluid flow.

The control logic is implemented using set and reset instructions to control the solenoid valves and pump motors. The distinction between each operating mode lies in the combination of valves and motors activated.

Additionally, an OFF control logic is implemented to stop the pump system by interrupting the operating current. Similar to the other configurations, this function utilizes the reset instruction.

c. Analog Output Processing

The analog output processing in the PLC utilizes the Norm_X and Scale_X instructions. Five control inputs are defined to regulate the valve opening at levels of 0, ¼, ½, ¾, and full opening.

The valve control is implemented using a move instruction, where the input is defined as a voltage value in decimal form, and the output is directed to the proportional valve. The voltage range is set between 1 V and 5 V, in accordance with the proportional valve specifications.

Based on this configuration, the corresponding decimal values are obtained as Table 4.

d. Analog Input Processing

The following describes the programming of sensors using analog inputs:

1. Flow Meter Programming

   The flow meter signal is processed using the Norm_X and Scale_X instructions to read the analog input %IW64. The Norm_X instruction converts the input range of 0–5 V into a normalized value, while Scale_X maps it to a range of 0–40. The Norm_X function is configured as int-to-real, generating an intermediate output (#temp_fm), which is then processed by the Scale_X function (*real-to-real*) to produce the final flow rate value.
2. Vacuum Sensor Programming

The vacuum sensor is processed similarly using Norm_X (int-to-real) and Scale_X (real-to-real) instructions, with %IW132 assigned as the input channel. The output represents the suction pressure of the fluid flow.

3. Pressure Sensor Programming

   The pressure sensor processing follows the same approach as the vacuum sensor, utilizing Norm_X and Scale_X instructions. The difference lies in the input channels, which include %IW134, %IW136, and %IW138. The resulting output represents the pressure within the fluid flow.

Table 4. Proportional Valve Opening Levels

Opening Level	Voltage	Decimal Value
0	1V	2765
½	2V	5530
¼	3V	8295
¾	4V	11060
1	5V	13825

2.2.4 Human Machine Interface (HMI) Programming

The development of the HMI involves several stages, as described below:

a. Selection of Interface Components

   The HMI interface is designed by defining various graphical components required to represent the pump installation system.

b. HMI and Control System Configuration

   Prior to interface design, the configuration between the control system and the HMI must be established to ensure proper communication and data exchange.

The following figure illustrates the HMI display during the operation of the pump under single, series, and parallel configurations.

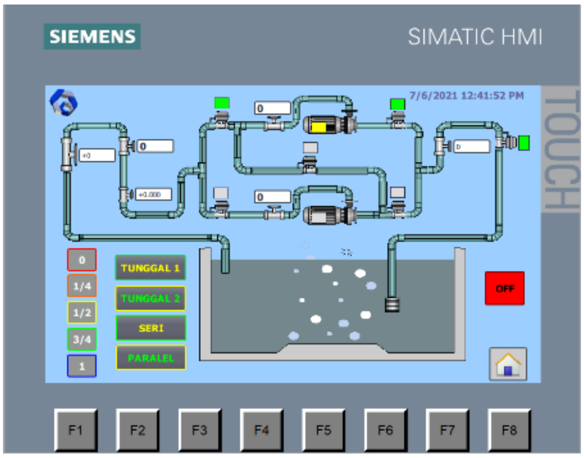

Fig. 4. Operation of single pump configuration 1

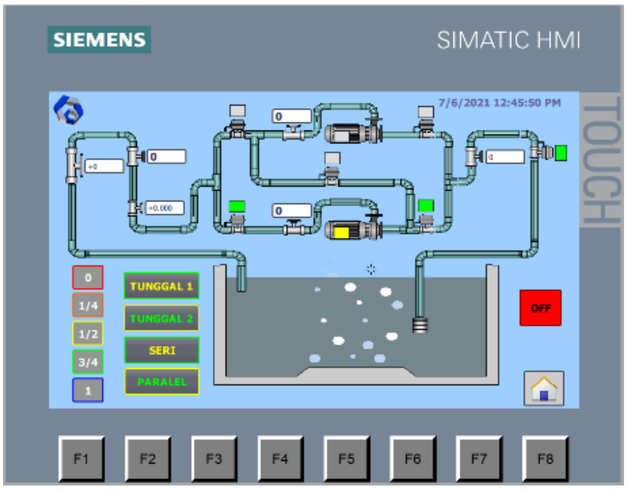

Fig. 5. Operation of single pump configuration 2

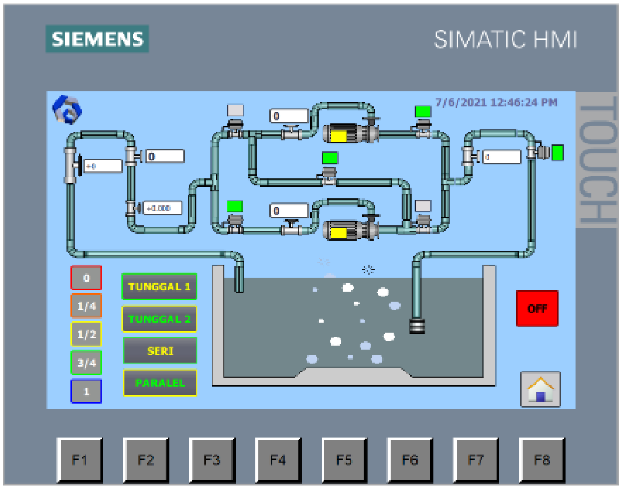

Fig. 6. Operation of series pump configuration

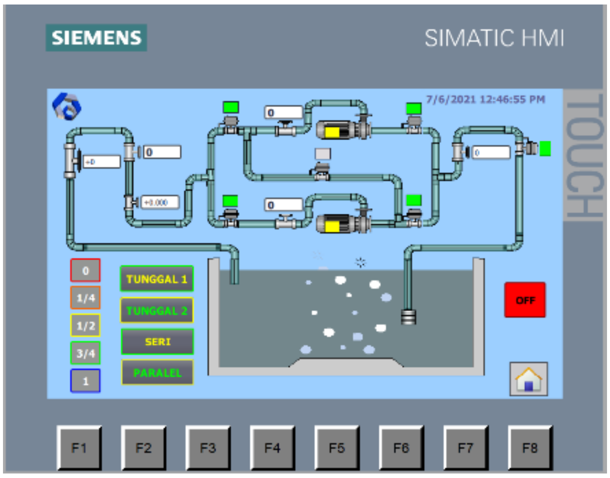

Fig. 7. Operation of parallel pump configuration

2.3 System Implementation

At this stage, the system is initially developed in smaller program modules, referred to as units, which are subsequently integrated in the later stages. Each unit is developed and tested for functionality through unit testing. The schematic diagrams designed in the system design phase are then implemented and translated into programs in accordance with the defined process flow. The implementation of the pump installation teaching aid control system is carried out incrementally, accompanied by continuous testing to ensure that all specified requirements are fulfilled.

2.4 System Integration and Testing

System integration is the stage in which all developed components are combined, including the assembly of hardware components and the integration between hardware and software (interface). Following this process, comprehensive system testing is conducted to evaluate the conformity between the designed system and its actual implementation. The following figure illustrates the integrated pump installation teaching aid system.

2.5 Operation and Maintenance

This stage represents the final phase of the Waterfall method. The completed system is deployed for operation and subjected to regular maintenance.

3. Results and Discussion

3.1 Presentation of Research Results

3.1.1 System Implementation and Operation

The pump installation control system was successfully implemented using a PLC based architecture integrated with a Human Machine Interface (HMI). All system components, including sensors, actuators, and control modules, were properly configured and operated according to the design specifications.

The HMI provided real time monitoring and control of key system parameters, including flow rate, pressure, and pump operating modes. During operation, the system was able to run under all defined configurations single, series, and parallel without critical failure. The interface functioned reliably, allowing users to observe system behavior and perform control actions effectively.

3.1.2 System Performance under Operating Conditions

The system performance was evaluated by analyzing the relationship between valve opening and the resulting flow rate and pressure. The results indicate that the flow rate increases proportionally with valve opening, ranging from negligible values at 0% opening to approximately 18 L/min at full opening. Similarly, the system pressure increased progressively with valve opening, reaching approximately 260 kPa under maximum operating conditions. To further support these observations, experimental data at different valve opening levels are presented in Table 5.

Table 5. Flow Rate and Pressure under Varying Valve Openings

Valve Opening	Flowrate (L/min)	Pressure
0	0,2	51
¼	5,1	121
½	10,2	179
¾	14,3	224
1	17,9	261

Overall, the flow rate increased by approximately 18 L/min, while the pressure increased by approximately 210 kPa from minimum to maximum valve opening.

Performance testing under different pump configurations revealed distinct operational characteristics. In the single pump configuration, moderate flow rate and pressure were observed. The series configuration produced the highest pressure, reaching approximately 260 kPa, due to the cumulative effect of pump heads. In contrast, the parallel configuration generated the highest flow rate, reaching approximately 18 L/min, as a result of flow distribution across multiple flow paths.

These results demonstrate that the system responds consistently to control inputs and operates in accordance with expected fluid behavior. Each experiment was repeated multiple times under consistent operating conditions, and the results showed stable and repeatable behavior with minimal variation.

3.1.3 Measurement Accuracy and Dynamic Response

The performance of the measurement system was evaluated by comparing sensor readings with reference values. The pressure and flow sensors achieved an average accuracy of approximately 95%, indicating reliable performance within the specified operating range. Minor fluctuations in sensor readings were observed but remained within acceptable engineering tolerances.

The dynamic response of the system was also assessed. The results show that the system required approximately 1–2 seconds to reach steady state conditions following changes in valve position. This response time is influenced by PLC processing cycles, analog signal conversion, and HMI communication delays.

Overall, the system demonstrates stable measurement performance and acceptable responsiveness for real time monitoring and control applications.

3.2 Analysis of Findings

The results indicate that the developed control system exhibits stable and predictable behavior under varying operating conditions, directly addressing the objective of this study to design and evaluate an HMI based pump control system. The proportional increase in flow rate with respect to valve opening confirms that the control mechanism effectively regulates fluid flow. This behavior occurs due to the reduction in flow resistance as the valve opening increases, allowing a greater volume of fluid to pass through the system.

Similarly, the observed increase in pressure with valve opening reflects consistent energy transfer within the fluid system. In the series pump configuration, the significant increase in pressure confirms the theoretical principle that pump heads are additive when pumps operate sequentially. In contrast, the parallel configuration produces higher flow rates due to flow distribution across multiple paths, reducing overall system resistance. These findings are consistent with established fluid dynamics principles and align with previous studies on centrifugal pump systems and fluid control mechanisms.

The measured sensor accuracy of approximately 95% indicates that the selected instrumentation performs within acceptable engineering tolerances. This relatively high accuracy can be attributed to the appropriate selection of sensor ranges based on theoretical calculations, ensuring that measurements are taken within optimal operating regions. However, minor fluctuations observed in the sensor readings suggest the presence of electrical noise or transient flow instability. Such variations are commonly reported in analog based measurement systems and highlight the importance of signal conditioning in control applications.

The system response time of 1–2 seconds reflects the combined effects of PLC scan cycles, analog-to-digital conversion, and HMI communication delays. While this response time is sufficient for monitoring and educational applications, it may be considered relatively high for high-speed industrial control systems. This indicates a trade-off between system complexity and responsiveness.

Compared to conventional manual measurement methods, the use of an HMI based system provides improved data consistency and reduced human error. This supports previous findings that digital monitoring systems enhance data reliability and operational efficiency in engineering applications. Furthermore, the integration of real time visualization offers additional value in educational contexts, as it enables users to directly observe the relationship between control inputs and system responses.

Overall, the findings provide important insights into the effectiveness of integrating PLC based control with HMI visualization. The system not only meets functional requirements but also demonstrates its potential as an interactive learning tool, bridging theoretical concepts and practical implementation.

3.3 Implications of the Results

The findings of this study provide several important implications for both engineering applications and educational system development.

From a technical perspective, the results demonstrate that the integration of a PLC based control system with an HMI interface is capable of providing reliable and real-time monitoring of fluid parameters.

The stable relationship between valve opening, flow rate, and pressure indicates that the system can effectively replicate fundamental fluid control behavior. This suggests that similar architectures can be applied in small to medium scale industrial systems where cost effective and modular control solutions are required.

Furthermore, the observed sensor performance, with an accuracy of approximately 95%, highlights the importance of proper sensor selection based on theoretical operating ranges. This implies that system reliability can be significantly improved when component specifications are aligned with expected working conditions. The findings also emphasize the role of analog signal processing in determining overall system performance, particularly in terms of response time and measurement stability.

From an educational perspective, the implementation of HMI based visualization offers significant advantages over conventional manual measurement methods. The ability to monitor system parameters in real time enables users to directly observe the relationship between control inputs and system outputs. This enhances conceptual understanding of fluid dynamics and control systems, particularly in topics such as pressure flow relationships and pump configurations.

In addition, the system supports interactive learning by allowing users to experiment with different operating conditions, such as valve openings and pump configurations. This contributes to improved engagement and learning efficiency, as users can immediately observe the consequences of their actions. Therefore, the developed system not only serves as a control and monitoring tool but also as an effective educational platform that bridges theoretical knowledge and practical application.

3.4 Limitations of the Study

Despite the promising results obtained in this study, several limitations should be acknowledged as they provide direction for further improvement and future research.

First, the system relies on analog sensors, which are inherently susceptible to electrical noise, signal drift, and environmental disturbances. Although the measured accuracy reached approximately 95%, minor fluctuations were still observed during operation. Future work should focus on improving measurement reliability through the implementation of digital sensors, signal filtering techniques, or noise reduction methods to enhance data stability.

Second, the system response time, measured at approximately 1–2 seconds, may not be adequate for high speed industrial control applications. This limitation is mainly influenced by PLC scan cycles, analog to digital conversion processes, and communication delays between the PLC and HMI. Future improvements may include optimizing control algorithms, utilizing faster communication protocols, or employing higher-performance controllers to reduce system latency.

Third, the experimental evaluation was conducted under controlled laboratory conditions, which may not fully represent real industrial environments. Factors such as fluctuating loads, fluid turbulence, and external disturbances were not extensively considered in this study. Therefore, future research should involve testing the system under more complex and dynamic conditions to evaluate its robustness and scalability in real world applications.

In addition, the current system operates primarily under an open loop control approach and does not incorporate advanced control strategies such as closed-loop feedback control, PID tuning, or adaptive control methods. The integration of such techniques in future work could significantly improve system stability, accuracy, and responsiveness, particularly under varying operating conditions.

Finally, this study does not include a comprehensive comparison with other control systems or alternative technological approaches. Future studies should consider benchmarking the proposed system against existing solutions to provide a more rigorous evaluation of its performance and effectiveness.

Overall, addressing these limitations will not only improve system performance but also expand the applicability of the proposed control system in both industrial and educational contexts.

4. Conclusion

This study successfully developed an HMI-based control and monitoring system for a pump performance teaching module by integrating a PLC with real-time visualization. The system enables interactive valve control and effective monitoring of pressure and flow rate. The results demonstrate that the system operates in accordance with fluid mechanics principles, where the series configuration produces the highest pressure due to cumulative pump head, and the parallel configuration generates the highest flow rate through flow distribution. The system shows consistent responses to control inputs, with an accuracy of approximately 95% compared to conventional instruments and an average response time of 1–2 seconds, indicating reliable performance for monitoring and educational purposes.

From an educational perspective, the integration of HMI improves learning effectiveness by approximately 20% through reduced observation time and improved data interpretation. The main contribution of this study lies in the development of a modular and interactive system that integrates control, monitoring, and visualization into a single platform. Despite these contributions, limitations remain in sensor precision, response time, and the absence of advanced control strategies. Future work will focus on incorporating remote operability features to enable online pump performance testing, thereby expanding the system's applicability in remote learning environments.

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