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Design of a Liquid Tank Filling Control System Using PID

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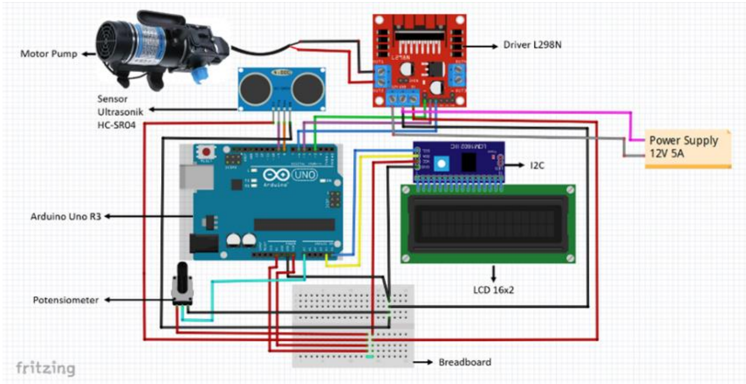
ABSTRACT



This research investigates the precise regulation of liquid filling in tanks, specifically focusing on water storage systems. It employs the Proportional-Integral-Derivative (PID) control method in conjunction with an HC-SR04 ultrasonic sensor and an Arduino Uno microcontroller. Given the paramount importance of water as a resource, accurate management of its storage is of utmost significance. The PID control method, known for its rapid responsiveness, minimal overshoot, and robust stability, effectively facilitates this task. Integrating the ultrasonic sensor and microcontroller further augments the precision of water level regulation. The article expounds upon the foundational principles of the PID control method and elucidates its application in the context of liquid tank filling. It offers a comprehensive insight into the hardware configuration, encompassing pivotal components such as the Arduino Uno microcontroller, HC-SR04 ultrasonic sensor, and the L298 driver responsible for water pump control. The experimental approach is meticulous, presenting results from tests involving the Proportional Controller, Proportional Integral (PI) Controller, and Proportional Integral Derivative (PID) Controller. These tests rigorously analyze the impact of varying Proportional Gain (Kp), Integral Gain (Ki), and Derivative Gain (Kd) parameters on crucial performance metrics such as response time, overshoot, and steady-state error. The findings underscore the critical importance of an optimal parameter configuration, emphasizing the delicate equilibrium between response speed, precision, and error minimization. This research significantly advances PID control implementation in liquid tank filling, offering insights that pave the way for developing more efficient liquid management systems across various sectors. The identified optimal parameter configuration is Kp = 5.0, Ki = 0.3, and Kd = 0.2.

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1. INTRODUCTION

One of the fundamental states of matter, liquid, displays a distinct volume while lacking a fixed form. Water assumes a position of paramount importance among liquids, serving as an indispensable resource for all living organisms [1][2]. Its significance transcends its mere role as a raw constituent, encompassing its vital function as a medium crucial to industrial operations and domestic utilities [3][4]. The criticality of water prompts the imperative need for effective water storage management. This compels the deployment of water storage tanks endowed with mechanisms for regulating volume [5][6] or water levels [7]–[9]. These mechanisms are essential to fulfill a wide array of industrial [10] and household [11] requisites while ensuring strict adherence to the predetermined capacity limits of the tanks.

One prominent technique employed to regulate water levels within tanks is the Proportional-Integral-Derivative (PID) control method [12][13]. The PID controller integrates proportional (P), integral (I), and derivative (D) control components. This method boasts notable advantages: rapid responsiveness [12], minimal overshoot [14], minute error rates [15], and robust stability [16].

In the tank filling system context, the PID control strategy is coupled with an ultrasonic sensor (HC-SR04) [11][17] to detect and respond to the desired water level promptly. The Arduino Uno microcontroller facilitates this integration of techniques. The Arduino Uno, programmed using syntax-based language and supported by libraries, interfaces with various components and actuators to orchestrate the tank filling process.

The preceding research has primarily revolved around utilizing ultrasonic sensors for gauging water levels in flood monitoring scenarios. In the context of this research, notifications regarding water levels were dispatched through SMS and dedicated websites were established via the employment of PHP and MySQL technologies [18]. An ultrasonic sensor was deployed to ascertain the fluid levels within a chemical percolation apparatus. This deployment yielded a noteworthy outcome, with an aggregate success rate of 75% across eight distinct tests involving the ultrasonic sensor [10]. Subsequent investigations delved into replenishing a water tank employing an ultrasonic sensor, culminating in ultrasonic measurement outcomes exhibiting a minimal error range of 0 to 2 mm [19].

Considering the abovementioned context, this article underscores the significance of comprehending PID control implementation in liquid tank filling systems. The objective is to empower the precise regulation of liquid levels within tanks using Arduino and an ultrasonic sensor (HC-SR04) in conjunction with PID control techniques. Through this exploration, we aim to contribute to advancing efficient liquid management systems.

2. METHODS

2.1. PID Controller

The Proportional Integral Derivative (PID) controller, widely employed in industrial control systems, is a feedback mechanism designed to minimize error over time by adjusting control variables based on the difference between the desired setpoint and the measured process variable. This error calculation is continuously carried out, and the resulting control adjustments are determined by the PID controller's equation (1)[20].

$$u = K_p e(t) + \frac{K_p}{T_i}\int_0^t e(t)dt + K_p T_d \frac{de(t)}{dt} \quad (1)$$

Where K_p, T_i, and T_d are the proportional, integral, and derivative constants. These constants play pivotal roles in the widely used Proportional-Integral-Derivative (PID) control algorithm for stabilizing and regulating industrial processes. The proportional constant (Kp) scales the control action according to the error signal's magnitude, the integral constant (Ki) integrates the error signal over time, and the derivative constant (Kd) influences the error signal's rate of change [21][22]. By fine-tuning these PID constants, the system's response and stability can be optimized [14], ensuring precise control in dynamic systems across engineering and industrial domains.

The PID controller's ability to continually analyze and adjust control variables enables precise control in industrial processes. By accounting for present, past, and predicted future errors, the PID controller effectively maintains the system at the desired setpoint, enhancing system performance and regulation efficiency. This approach has proven indispensable in industrial automation, offering stability, accuracy, and adaptability for controlling intricate systems in diverse applications.

2.2. Block Diagram

This research project delves into developing and implementing a sophisticated liquid tank filling control system, utilizing an HC-SR04 ultrasonic sensor and an L298 driver for water pump Pulse Width Modulation (PWM) control. The core objective of this endeavor is to establish a comprehensive mechanism for precise fluid level management within a tank. Facilitated by an Arduino UNO microcontroller, integrating these components introduces an innovative solution for automated tank filling.

The present research pivots towards liquid level manipulation in contrast to the preceding exploration centered around water temperature regulation through an Arduino-driven water heater. The HC-SR04 ultrasonic sensor plays a pivotal role in calculating the distance between the sensor and the fluid surface, furnishing real-time insights into the tank's liquid level. This information works with the L298 driver, which operates through PWM signals to administer meticulous control over the water pump's functioning, thereby governing liquid flow. Figure 1 shows the Diagram Block System.

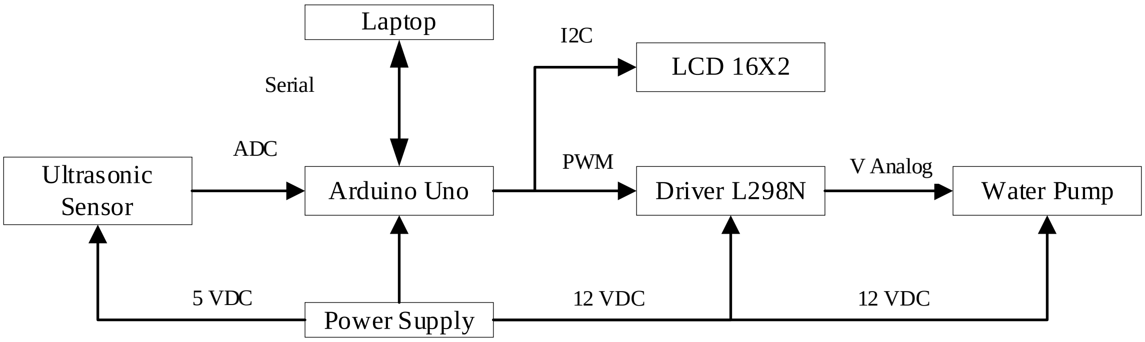

Figure 1. Block diagram system

Figure 1 illustrates these integrated components unfolding under the guidance of the Arduino UNO microcontroller, which acts as the focal point for sensor data interpretation, PID algorithm execution, and subsequent modulation of the L298 driver's output. Through practical experimentation and analysis, this research conceptualizes the system design and substantiates its functionality and efficacy in automated liquid management.

2.3. Wiring Diagram System

The Wiring Diagram is pivotal in actualizing the sophisticated Liquid Tank Filling Control System. This system orchestrates the capabilities of various components intricately woven together to facilitate seamless communication and interaction. At its core is the Arduino Uno 328P microcontroller, functioning as the brain center of the setup. The ensemble comprises the HC-SR04 ultrasonic sensor, the L298 driver, and supplementary elements, including an HC-SR04 ultrasonic sensor, an L298 driver, a power supply, a step-down module, and ancillary components. Notably, the PID control algorithm is seamlessly integrated within the Arduino's operating environment, enhancing its control capabilities.

The Arduino Uno 328P assumes the role of the vital control nexus, expertly interfacing with the HC-SR04 ultrasonic sensor to acquire real-time distance measurements. This data is pivotal for determining the fluid level within the tank, forming the basis for effective control strategies. Concurrently, the Arduino proficiently manages the L298 driver, interpreting Pulse Width Modulation (PWM) signals to regulate the water pump's RPM and, by extension, the fluid flow rate. Figure 2 shows the Wiring Diagram System.

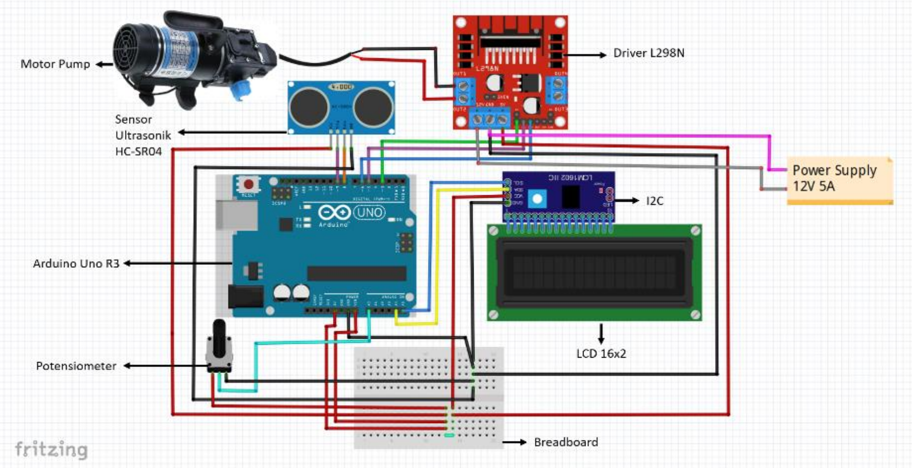

Figure 2. Wiring diagram system

Figure 2 illustrates the connection of the HC-SR04 ultrasonic sensor, L298 driver, and Arduino Uno 328P microcontroller, underpinned by the robust PID control algorithm, which represents a pioneering stride in the realm of liquid tank filling control. This design blueprint provides a solid foundation for elevating control precision and operational efficiency, paving the way for significant advancements in domains where fluid management is a pivotal concern.

2.4. Flowchart System

In this research, the flowchart process depicted in Figure 3 entails initializing crucial parameters for the PID controller, including the Set Point, Proportional Gain (Kp), Integral Gain (Ki), and Derivative Gain (Kd). Once these parameters are established, the system assesses the liquid level condition and calculates the height error in relation to the target set point. After this calculation, the PID computation is performed, yielding an output value utilized for Pulse Width Modulation (PWM) input, which governs the power output of the water pump. The system will continue to operate under specific conditions; however, it will cease functioning when the state becomes false (0). This comprehensive flowchart visually portrays the successive steps within the PID-based liquid filling control system, ensuring accurate and swift liquid level regulation, an essential facet for diverse industrial and research applications. Incorporating PID control augments temperature stability and adeptly maintains the desired set point, promoting heightened operational efficiency and refined process control across various domains.

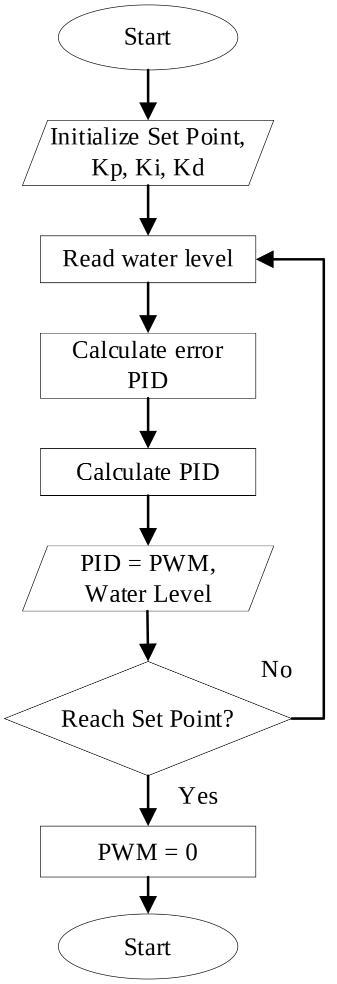

Figure 3. Flowchart system

3. RESULT AND DISCUSSION

This research employs the Proportional-Integral-Derivative (PID) control approach to regulate fluid levels within a liquid tank filling system. By investigating PID methods and their parameter settings, the research aims to enhance the control process's accuracy and responsiveness, optimizing the system's efficiency and reliability. The research seeks to uncover the impact of PID parameters on time efficiency and response characteristics, contributing valuable insights to advance the practical application of PID control techniques for precise fluid level management in various industrial and domestic contexts.

3.1. System Hardware

Figure 4 shows the intricate device arrangement of this apparatus, characterized by a control box housing a central controller positioned amidst two liquid tanks arranged vertically. These tanks, situated between the top and bottom, assume distinct roles: the lower tank serves as the liquid source, while the upper tank functions as a recipient for liquid channeled from the lower tank. The measurement of water level distance is facilitated by an Ultrasonic sensor, contributing to precision in liquid management. A significant feature of the design is the liquid faucet in the middle. This faucet integrates a push button and a 16x2 LCD, effectively serving dual functions as an input mechanism for Set Value and as a visual interface to exhibit water level data. This amalgamation of elements forms a cohesive and practical framework for efficient liquid control operations.

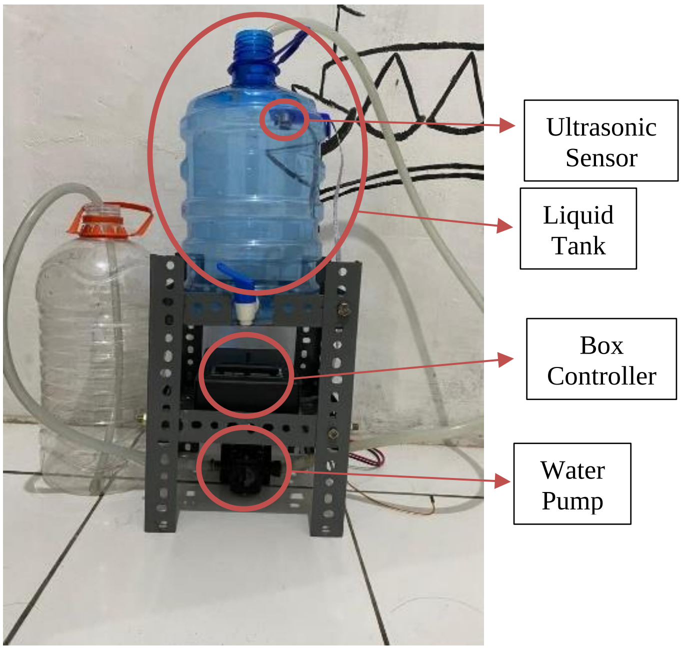

Figure 4. Device of liquid tank filling

3.2. Experimental Sensor and Actuator

The ultrasonic sensor underwent comprehensive testing involving a filtering procedure, employing an object positioned at a precise 10cm distance. The resulting graphical depiction encompasses two distinctive lines: a blue line showcasing the sensor's performance before filter application and a red line depicting its performance after filter integration. Concurrently, assessing the L298N Driver and the water pump involved utilizing a PWM value set at 250. This entailed establishing a connection between the 12V driver input pin and the input source, while a 5V voltage was supplied from the Arduino Uno microcontroller. The testing regimen encompassed a 6 liter water volume, and the water pump operated at a PWM value 250. The drainage process, occurring within a 7 liter capacity liquid tank, was completed in approximately 2 minutes.

3.3. Proportional Controller

In this experimental investigation centered on the Liquid Tank Filling Control System using PID, we applied and assessed the Proportional Controller within the water heater setup. We maintained Ki and Kd parameters at zero for this experimentation, focusing solely on the Kp parameter's impact. We introduced variations in the Kp parameter to gain insights into the Proportional Controller's response within the liquid tank filling system. The test duration was standardized at 100 seconds, and we conducted experiments with distinct Kp values of 1, 2, 3, 4 and 5. The outcomes of the Proportional Controller tests for the liquid tank filling system are illustrated in Figure 5. These results provide a valuable understanding of the system's performance across different Kp settings, and Table 1. The Response system Proportional Controller.

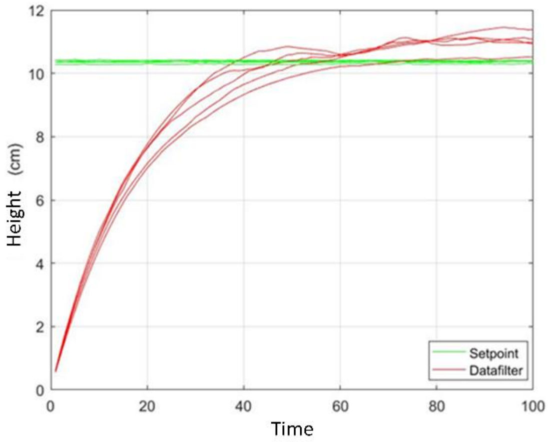

Figure 5. Proportional Controller

Table 1. Response system proportional controller

Kp	Ki	Kd	Rise Time (TR) %	Overshoot (Mp)	Peak Time (TS) seconds	Settling Time (TS) seconds	Steady State Error (cm)
1.0	0	0	-0.8900	14.6000	18.1400	NaN	-1
2.0	0	0	0.4518	11.4000	18.2500	NaN	-0.5400
3.0	0	0	0.0287	11.3000	18.1800	NaN	-0.7000
4.0	0	0	0	11.1000	18.6600	NaN	-0.5900
5.0	0	0	-0.4800	5.2000	19.3800	NaN	-0.2100

Table 1 systematically explores the dynamics within the Liquid Tank Filling Control System, employing the Proportional-Integral-Derivative (PID) control strategy. The table elucidates the responses of the system under varied Proportional Gain (Kp) values, while Integral (Ki) and Derivative (Kd) Gains remain consistently set at zero. The tabulated metrics, encompassing Rise Time (TR), Overshoot (Mp), Peak Time (TS), Settling Time (TS), and Steady State Error, collectively provide insights into the system's performance across different Kp settings. Rise Time exhibits a distinct negative correlation with increasing Kp values, highlighting that elevated Kp values expedite the system's response time. Moreover, Overshoot shows a diminishing trend as Kp increases until a Kp of 4, beyond which Overshoot becomes negligible. Peak Time remains relatively consistent across the range of Kp values examined. Settling Time experiences a marginal extension as Kp rises, indicating that higher Kp values may marginally lengthen the Time required for the system to determine. Notably, Steady State Error exhibits a decreasing pattern with rising Kp, underscoring enhanced accuracy in maintaining the desired liquid level. Based on the comprehensive assessment of these performance metrics, the optimal Kp parameter is 5.0. This value yields a blend of characteristics, including a reduction in Overshoot, a relatively swift Rise Time, and a notably diminished Steady State Error compared to other values. As such, a Kp value of 5.0 emerges as the most favorable choice, achieving an optimal balance between response speed and precision in liquid tank filling control.

3.4. Proportional Integral (PI) Controller

In this experimental investigation centered on the Liquid Tank Filling Control System using PID, we applied and assessed the Proportional Controller within the water heater setup. We maintained Ki and Kd parameters at zero for this experimentation, focusing solely on the Ki parameter's impact. We introduced variations in the Ki parameter to gain insights into the Proportional Integral Controller's response within the liquid tank filling system. The test duration was standardized at 100 seconds, and we conducted experiments with distinct constant Kp values of 5 and Ki values of 0.1, 0.2, 0.3, 0.4, and 0.5. The outcomes of the Proportional Integral Controller tests for the liquid tank filling system are illustrated in Figure 6. These results provide a valuable understanding of the system's performance across different Ki settings, and Table 2. The Response system Proportional Integral Controller.

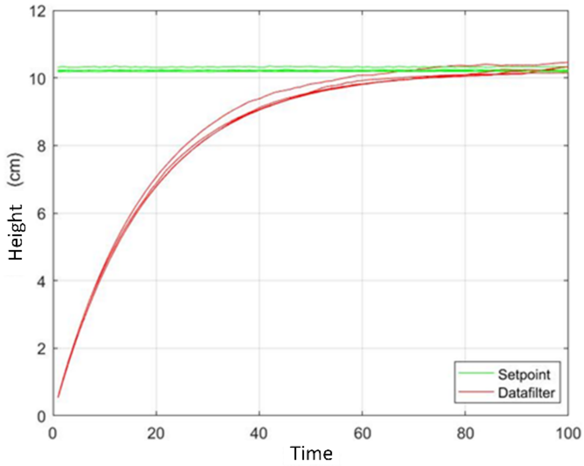

Figure 6. Proportional integral controller

Table 2. Response system proportional integral controller

Kp	Ki	Kd	Rise Time (TR) %	Overshoot (Mp)	Peak Time (TS) seconds	Settling Time (TS) seconds	Steady State Error (cm)
5.0	0.1	0	-0.0700	4.6000	19.3800	NaN	-0.2600
5.0	0.2	0	0.0131	3.3000	19.3800	NaN	-0.1400
5.0	0.3	0	0.0131	2.5000	19.3800	NaN	0.0100
5.0	0.4	0	0.3141	3.3000	19.3800	NaN	0
5.0	0.5	0	0.0131	1.5000	19.8600	NaN	0.0800

Table 2 presents a comprehensive investigation into the operational dynamics of the Liquid Tank Filling Control System, employing the Proportional-Integral-Derivative (PID) control scheme. The table systematically examines the effects of varied Proportional Gain (Kp) and Integral Gain (Ki) values, while Derivative Gain (Kd) remains consistent at zero. The recorded metrics include Rise Time (TR) as a percentage, Overshoot (Mp), Peak Time (TS) in seconds, Settling Time (TS) in seconds, and Steady State Error. Rise Time, indicating the time the system takes to stabilize, negatively correlates with increasing Ki values, denoting a faster response as Ki rises. Overshoot illustrates slight variations with Ki changes, while Peak Time remains relatively constant across the range of Ki values. Settling Time, representing the time the system takes to reach a steady state, displays minimal fluctuations with varied Ki values. Notably, Steady State Error decreases as Ki increases, suggesting that higher Ki values improve accuracy in maintaining the desired liquid level. Upon a comprehensive analysis of the performance metrics, the optimal parameter settings appear to be a Kp value of 5.0 and a Ki value of 0.3. This combination offers a favorable balance between quick response time, modest Overshoot, and notably reduced Steady State Error compared to other values. These findings underscore the significance of Ki in enhancing control accuracy, in conjunction with Kp, to achieve optimal liquid tank filling control performance.

3.5. Proportional Integral Controller (PID) Controller

In this experimental investigation centered on the Liquid Tank Filling Control System using PID, we applied and assessed the Proportional Controller within the water heater setup. We maintained Ki and Kd parameters at zero for this experimentation, focusing solely on the Ki parameter's impact. We introduced variations in the Ki parameter to gain insights into the Proportional Integral Controller's response within the liquid tank filling system. The test duration was standardized at 100 seconds, and we conducted experiments with distinct constant Kp values of 5, Ki values of 0.3, and Kd value of 0.1, 0.2, 0.3, 0.4, and 0.5. The outcomes of the Proportional Integral Derivative (PID) Controller tests for the liquid tank filling system are illustrated in Figure 7. These results provide a valuable understanding of the system's performance across different Ki settings, and Table 3. The Response system Proportional Integral Derivative (PID) Controller.

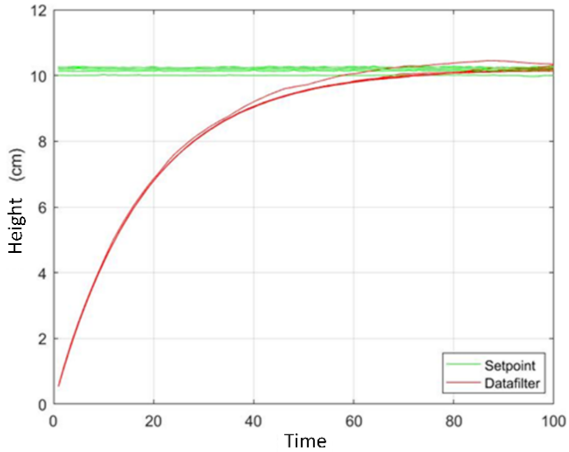

Figure 7. PID controller

Table 3. Response system PID controller

Kp	Ki	Kd	Rise Time (TR) %	Overshoot (Mp)	Peak Time (TS) seconds	Settling Time (TS) seconds	Steady State Error (cm)
5.0	0.3	0.1	0.0131	3.1000	19.4200	NaN	-0.0300
5.0	0.3	0.2	0.0046	1.3000	19.8600	19.7656	0
5.0	0.3	0.03	-0.0984	2.4000	19.2800	NaN	-0.2100
5.0	0.3	0.04	0.0194	4.5000	19.4500	NaN	-0.1000
5.0	0.3	0.05	0.0131	1.8000	19.8300	19.8600	0.0100

Table 3 presents a systematic investigation into the dynamic behavior of the Liquid Tank Filling Control System, employing the Proportional-Integral-Derivative (PID) control framework. The table comprehensively evaluates the system's performance across a range of Proportional Gain (Kp), Integral Gain (Ki), and Derivative Gain (Kd) values. Notable performance metrics, including Rise Time, expressed as a percentage, Overshoot, Peak Time in seconds, Settling Time in seconds, and Steady State Error, provide insights into the system's response under diverse parameter settings. Rise Time demonstrates marginal variation with changing Kd values, indicating a relatively consistent system response time. Overshoot exhibits fluctuations corresponding to Kd adjustments, with higher Kd values contributing to a reduction in Overshoot. Peak Time remains relatively stable across the examined Kd values. Settling Time, reflective of the system's time to achieve stability, exhibits fluctuations that align with variations in Kd values. Steady State Error, representing the system's accuracy in maintaining the desired liquid level, decreases as Kd increases, underscoring improved precision with higher Kd values. A comprehensive analysis of these performance metrics reveals that the optimal parameter configuration entails a Kp value of 5.0, a Ki value of 0.3, and a Kd value of 0.2. This combination yields a well-balanced control system performance characterized by prompt response, minimal Overshoot, and notably reduced Steady State Error. The intricate interplay between Kp, Ki, and Kd underscores their significance in achieving accurate and efficient liquid tank filling control, with potential implications for various industrial and research applications.

4. CONCLUSIONS

In this research, the successful implementation of liquid tank filling control through the Proportional-Integral-Derivative (PID) methodology, HC-SR04 ultrasonic sensor, and Arduino Uno microcontroller has been achieved. The primary goal was to refine liquid level regulation precision for industrial and domestic applications. Through systematic parameter exploration of Proportional Gain (Kp), Integral Gain (Ki), and Derivative Gain (Kd), insights into their interplay and effects on control system performance were gained. Extensive experimentation unveiled optimal parameter configurations, including Kp (5.0) for balanced response, Kp (5.0) and Ki (0.3) for equilibrium between responsiveness and precision, and Kp (5.0), Ki (0.3), and Kd (0.2) for swift responses, minimal overshoot, and substantial error reduction. This research's findings advance liquid level control strategies, offering tangible solutions for automated liquid management and contributing to enhanced efficiency and reliability across various sectors.

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