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Design and Implementation of a Didactic Cascade Tank Level Control System

N. Pillay
Department of Electronic and Computer Engineering
Durban University of Technology
Durban, Kwa-Zulu Natal, Republic of South Africa
trevorpi@dut.ac.za

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***Abstract*— Engineering students in the field of industrial process control usually experience difficulty in assimilating theoretical concepts and its practical application. Typically, a laboratory practical based solely on computer driven software simulation offers the course facilitator a simple and cost effective solution to demonstrate control engineering fundamentals. The use of commercially available educational hardware kits may provide an improved learner experience but are relatively expensive. This paper describes the design and implementation of a low cost alternative to introduce realism into control education. The didactic system consists of dual cascaded tanks, continuous level sensors, a pump, a regulated power supply and an Arduino® MEGA2560 microcontroller connected to a computer. An automatic control system is designed in MATLAB SIMULINK™ and deployed to the proposed hardware system to ensure that the tank level reaches a desired set-point. Experimental results indicate that the embedded control system is beneficial in demonstrating practical process modelling techniques and satisfies automatic controller design objectives in a laboratory environment.**

Keywords—PID control, embedded control, real-time experimentation, process control engineering

I. Introduction

Achieving hands-on exposure to industrial control systems is vital to gaining a deeper understanding of theoretical engineering concepts taught in the class room. Generally, commercially available control engineering laboratory hardware specifically designed to satisfy this requirement are often too expensive. Furthermore, the proprietary components may require additional training in order to operate and maintain. To overcome these drawbacks, there have been several attempts at implementing "in-house" pilot scale process control laboratory solutions, see [1] – [6].

In the work of Åström and Östberg [1], a simple liquid level control experiment was proposed due to its effectiveness in demonstrating important control ideas such as; negative feedback control, process modelling, effects of process disturbances and measurement noise amongst others. The level process variable was chosen primarily because of its simplicity and efficacy in stimulating a learner's visual and auditory sensations. Importantly, it was non-hazardous and inexpensive to operate and maintain.

Reis et al. [2] and Sheng [3] proposed the use of an Arduino® microcontroller as the primary hardware platform to control liquid level to a desired user set-point (SP) in a pilot scale single tank system. The main focus of the laboratory experiments was the design of the control strategy, process dynamic modelling, Proportional, Integral and Derivative (PID) controller parameter tuning and analysis of the liquid level dynamic responses. Chabni et al. [4] evaluated the performance of a Fuzzy Logic (FL) control scheme in a water tank level using the Arduino® microcontroller. They observed that the FL system performed well when compared to the conventional PID control. Recently, Yumurtaci and Verim [5], applied complex control algorithms such as Artificial Neural Networks (ANN) and combined ANN-PID control schemes in a tank level control system.

Arrieta et al. [6] proposed the use of commercially available Programmable Logic Controller (PLC) and Human Machine Interface (HMI) hardware in their training system. The training system allowed undergraduate students to gain experience with the calibration of instrumentation devices and the integration of different technologies used in the control and automation of processes. This is the ideal situation, were actual industrial control and instrument equipment are used in the laboratory. This approach however, may not be feasible due the high cost of the industrial equipment and where laboratory space is limited.

To address these drawbacks, simulation software plays an important and fundamental role in the teaching and learning of a control engineering course. Tona [7] proposed teaching materials developed with Scilab and Scicos which are free and open source computing software. The Scilab software shares similarities to MATLAB™ as it is an interpreted matrix based language with built-in mathematics functions and libraries. Scicos is the associated dynamic modeler and simulator package. Tona [7] and Motta Pires and Rogers [8] demonstrated that flexible and visually appealing open source software can be used to reinforce basic concepts. This is beneficial, particularly when commercial mathematical software are unavailable.

In this study, a cascade dual tank liquid level system is used to demonstrate fundamental control engineering concepts with increasing complexity designed to stimulate student interaction during laboratory sessions. The system uses low cost hardware in which scalable control schemes can be designed and deployed in real time using MATLAB SIMULINK™.

This paper is organized as follows. In section II, the experimental laboratory equipment and mathematical modelling of the process are described. In section III, the software detail of

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the control is given. In section IV, the laboratory sessions and results are presented. The concluding remarks are provided in section V.

II. Prototype Description and System Modelling

A. Laboratory plant hardware description

The motivation for using two cascaded tanks is that the upper tank is characterized by a first order response, while the lower tank has a second order response [1]. This permits students to experiment with dissimilar process dynamics and investigate the responses of different types of automatic control approaches. The user can easily make adjustments to the system by using the MATLAB SIMULINK™ simulation environment in real time. Fig. 1(a) and Fig. 1(b) shows the system block diagram and the experimental dual tank liquid level control setup respectively.

Tank 1 connects to Tank 2 using a gravity drain outlet. Both cylindrical tanks have an internal diameter of 55mm and an outlet pipe diameter of 4mm. The bottom reserve tank holds liquid that is recycled through the arrangement using a 12 VDC pump. The pump pressure should be adequate to overcome the delivery pipe hydrostatic pressure during low flow rates. A driver module assembly (L298) is used to control the speed of the pump and receives a Pulse Width Modulated (PWM) signal from the Arduino® Mega2560 microcontroller board. Continuous liquid level measurement in both the tanks are achieved using a pressure sensitive Milone eTape® [9] which extends the entire length of each cylindrical tank which is 35cm in length. The level transducer exhibits a change in resistance as the liquid level fluctuates and is less susceptible to variations in process disturbances.

Conversion of the transducer resistance to a voltage signal is achieved by connecting the eTape® in the prescribed Wheatstone bridge connection. A standalone PC running MATLAB SIMULINK™ is connected to the Arduino® Mega2560 using a universal serial bus link.

B. Model description of the cascade tank level system

The double tank system depicted in Fig. 2 is described by the following set of mass balance equations:

$$\frac{dh_1}{dt} = \frac{K_m}{A_1}V_m - \frac{a_1}{A_1}\sqrt{2gh_1} \tag{1}$$

$$\frac{dh_2}{dt} = \frac{a_1}{A_1}\sqrt{2gh_1} - \frac{a_2}{A_2}\sqrt{2gh_2} \tag{2}$$

where, h_1 and h_2 represent the height of the liquid level in tank 1 and tank 2 respectively. The cross sectional area of the cylindrical tanks are given by A and the effective tank outlets are denoted by a for each of the tanks. The pump has a gain constant given by K_m and the voltage applied to the device is represented as V_m. The gain constant can be easily determined by blocking tank 1 outlet and measuring the time it takes for the liquid to rise from minimum to maximum level points for a given pump voltage. The inlet flow rate into the upper tank is directly proportional to the applied pump voltage. Gravitational acceleration constant is denoted by g.

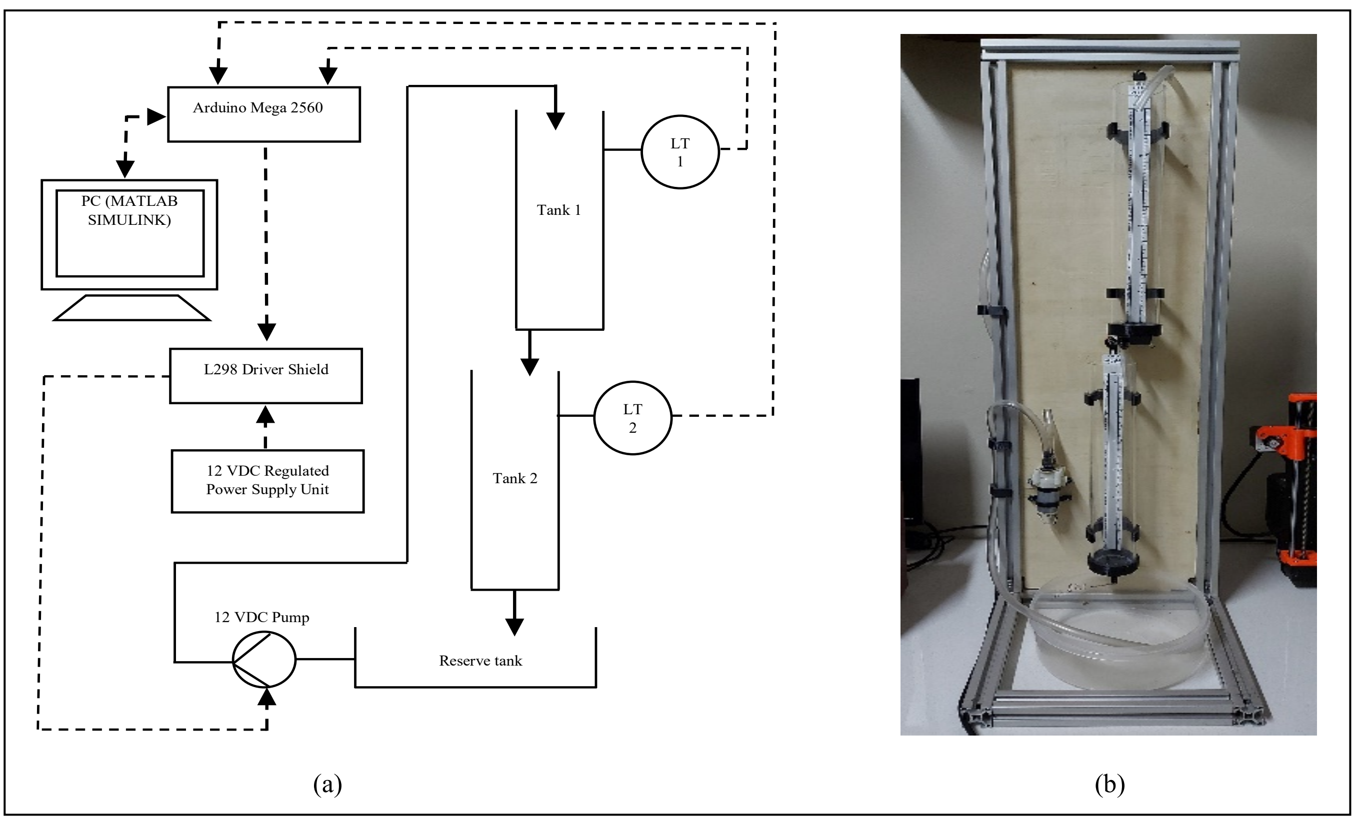

Fig. 1. Dual tank liquid level block diagram (a) and the experimental setup (b).

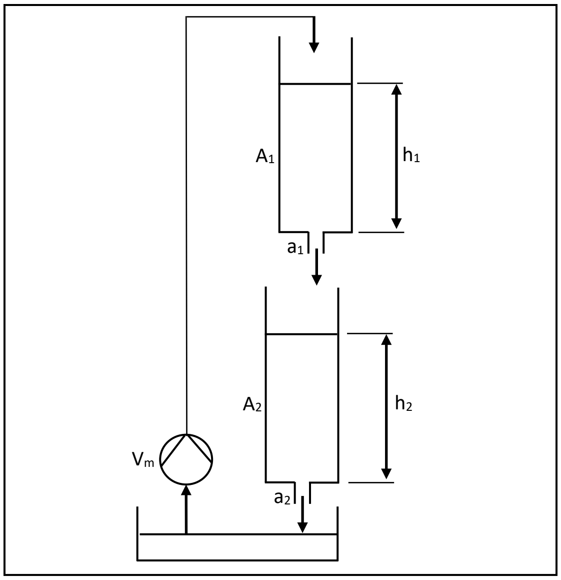

Fig. 2. Schematic diagram of a two tank cascade system.

The process dynamics can be linearized and described by the following Laplace transfer functions:

$$\frac{H_1(s)}{U(s)} = \frac{K_p e^{-L_p s}}{(1+sT_{p1})} \quad (3)$$

$$\frac{H_2(s)}{U(s)} = \frac{K_p e^{-L_p s}}{(1+sT_{p1})(1+sT_{p2})} \quad (4)$$

where, K_p represents the open loop process gain which is a function of the pump gain, level transducer gain constant and the cross sectional area of the tank. Transportation lag time for the system is denoted by L_p. The process time constants for the respective tanks are given by T_{p1} and T_{p2}. The controllability ratio $\frac{L_p}{T_p}$ gives a measure of difficulty in controlling the process. $\frac{L_p}{T_p} > 1$ are dead time dominant systems and are not considered in this study due to the tank dynamics of the control setup.

III. Software Implementation of the PID Controller

A. PID controller description.

PID controllers are commonly used in numerous industrial process control applications [10, 11]. This is primarily due to its simple and transparent algorithm which can be fine-tuned for many types of processes. The main feature of the PID controllers is the capacity to reduce steady state errors and anticipate future output changes when all terms are used in the control algorithm. Furthermore, it can be used for set-point tracking or disturbance rejection control. The controller output provides a signal that is proportional to the error between the user set-point and the actual process variable, namely:

$$u(t) = K_c[e(t) + \frac{1}{T_i}\int_0^t e(t)\,dt + T_d \frac{d}{dt} e(t)] \quad (5)$$

where, $u(t)$ and $e(t)$ is the controller output and the negative feedback error signals respectively. K_c, T_i and T_d are the corresponding proportional gain, integral time constant and derivative time constant. Fig. 4 shows the PID control algorithm implemented in a closed loop feedback control system in MATLAB™ SIMULINK for the dual tank level control. The integral control action is clamped to prevent integral windup during output saturation and the sample rate is 0.1 seconds.

The student can enter the desired level set-point and change the feedback control for either tank 1 or tank 2. In addition, selection of set-point tracking or disturbance rejection can be made. An audible high level alarm gives the user an indication when the liquid level is excessive.

B. PID parameter selection.

Industrial controller parameter selection is imperative for optimum and robust control. The tuning procedure, if done manually, can be very tedious, time consuming and is dependent on the control practitioner experience [12]. The Ziegler-Nichols [13] open loop and ultimate cycle tuning methodology is widely known and has been successfully applied to common industrial processes with acceptable performance. A distinct advantage of this method is the simple tuning formulae and the relative ease with which it can be applied in practice. The tuning formulae represents an ideal starting point for students to obtain practical exposure to controller design in the laboratory. The Ziegler-Nichols open loop tuning formulae is shown in Table 1. The process characteristics can be acquired from graphical analysis of the open loop step response as shown in Fig.3. The values K_c, T_i and T_d are obtained from Table 1 and applied to the controller algorithm given by (5).

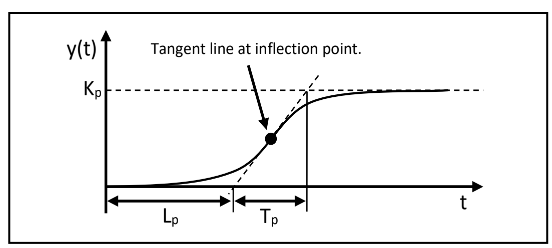

Fig. 3. Three parameter model estimation from the response curve.

TABLE I. Ziegler Nichols Open loop tuning rules

Controller type	Controller parameters		
	K_c	T_i	T_d
P	T_p/L_p	-	-
PI	$0.9T_p/L_p$	$3.3L_p$	-
PID	$1.2T_p/L_p$	$2L_p$	$0.5L_p$

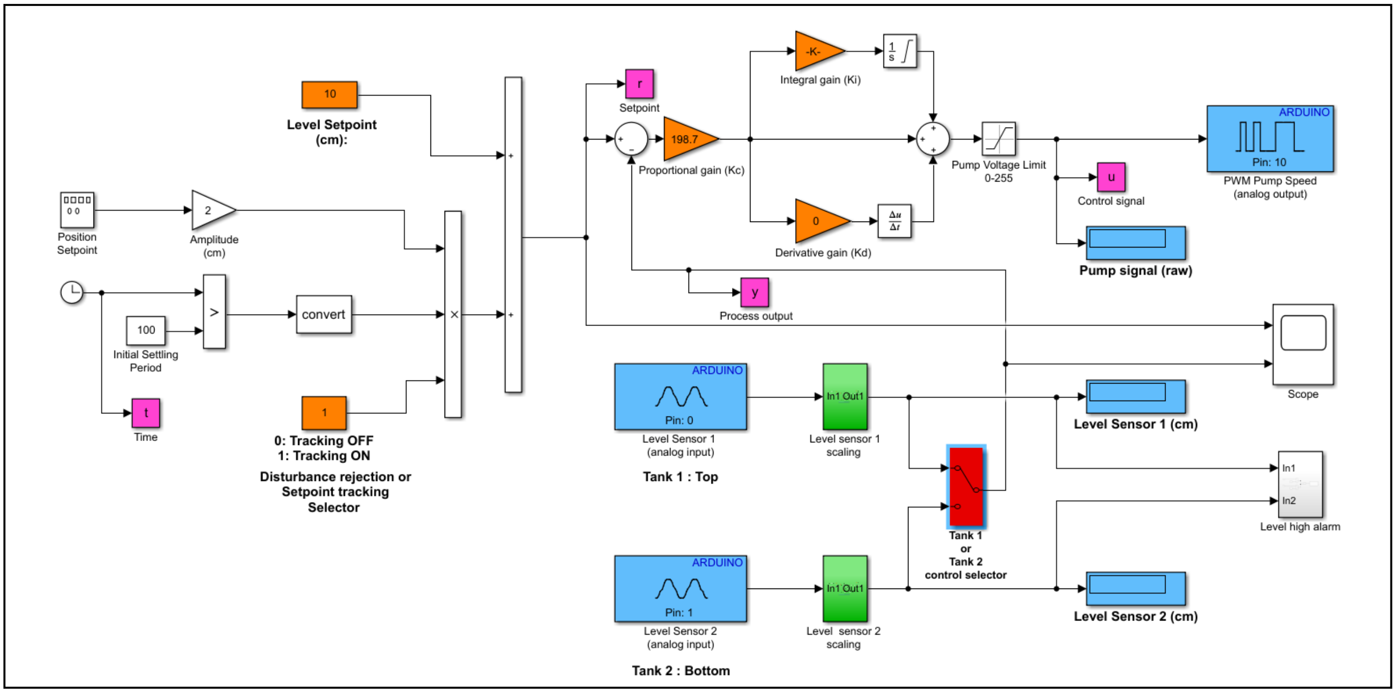

Fig. 4. Block diagram of the tank level control system in SIMULINK.

In addition, the Ziegler Nichols ultimate cycle or closed loop method [13] is considered in the laboratory experiments to allow students to explore different PID parameter settings and observe its effect in the control loop. This method however requires the value of K_c to be increased incrementally to achieve continuous closed loop oscillation with $T_i = inf$ and $T_d = 0$. This may cause lengthy time delays since the value of the ultimate gain (K_u) has to be determined experimentally. An improved methodology which uses a simple relay to drive the system into oscillation is given by [12]. Fig. 5(a) shows the inclusion of the relay device in the closed loop which is used as the pre-tuning phase for the controller design. From Fig. 5(b), the student is required to extract the critical period P_u , the process amplitude a_p and the relay output $2d$ to compute the ultimate gain:

$$K_u = \frac{4d}{\pi a_p} \tag{6}$$

Table 2 shows the Ziegler Nichols ultimate cycle PID tuning rules.

TABLE II. ZIEGLER NICHOLS ULTIMATE CYCLE TUNING RULES

Controller type	Controller parameters		
	K_c	T_i	T_d
P	$0.5K_u$	-	-
PI	$0.45K_u$	$\frac{P_u}{1.2}$	-
PID	$0.6K_u$	$\frac{P_u}{2}$	$\frac{P_u}{8}$

IV. Laboratory Sessions

A. Liquid level process characterisation.

In order to design a controller for the level process described in (3) and (4), the system transfer functions for each tank need to be determined. MATLAB™ provides an integrated model identification toolbox, “*systemIdentification*” that can be used to estimate the model parameters. However, this approach requires pre-processed input and output data and validation system information to be readily available. A simpler and pragmatic model estimation approach without the use of commercial software tools is the traditional process reaction curve methodology.

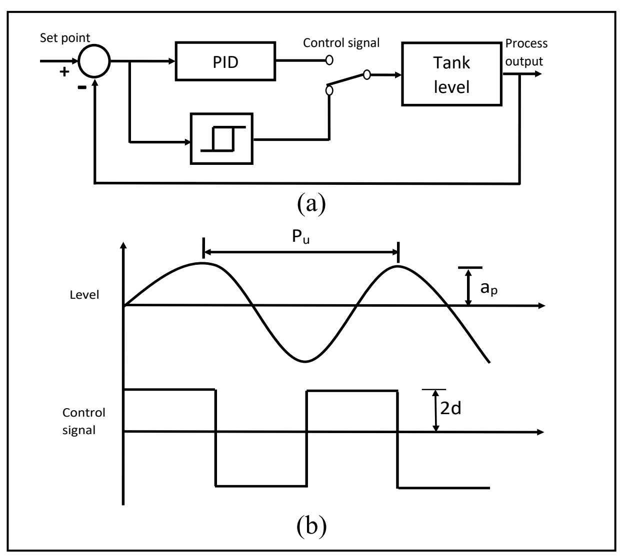

Fig. 5. Relay tuning pre-tuning phase (a) and the closed loop responses (b).

In this approach, the student can inject a step input voltage into the pump and observe the open loop level response for each tank. Fig.6(a) and Fig.6(b) illustrates the process reaction curves for tank 1 and tank 2 respectively. The responses are typical of a first order system with transportation delay and can represent a large number of real world industrial processes [10]. Students can evidently see the difference in process gain and the process time constants between the upper and lower tanks. As described in Fig. 3, the three parameter model can be conveniently extracted from the recorded open loop responses [13]. The process gain K_p is estimated by:

$$K_P = \frac{\Delta\, liquid\ level\ (cm)}{\Delta\, pump\ control\ signal\ (8\ bit)} \tag{7}$$

In this experiment, the 8 bit control signal to the pump was step changed and the liquid level was recorded until steady state was achieved. The tank parameters, transportation lag time L_p and process time constant T_p are graphically estimated by drawing a line tangential to the inflection point on the process reaction curve and noting its intersection with the time axis and the steady state value.

B. *Tank 1 level control experiments.*

Subsequent to the process characterization, students can perform the following experiments for tank 1:

i. Tune a P, PI and PID control for set point tracking using the Ziegler Nichols open loop tuning rules given in Table 1.

ii. Simulate a load disturbance by injecting a fixed volume of liquid into the tank during the control experiment.

iii. Examine the effect of using the PID control with a first order filter y_f to reduce process noise and prevent excessive derivative controller action on the pump. In this case, the control action is implemented as:

$$u(t) = K_c[e(t) + \frac{1}{T_i}\int_0^t e(t)\,dt - T_d\frac{dy_f}{dt}] \tag{8}$$

$$y_f = \left(\frac{1}{1+sT_d/N}\right)y \tag{9}$$

where, y is the process output and N is the noise filter constant. Typical values for N is in the range of 3-10 [14]. Without loss of generality, $N = 10$ is used.

C. *Tank 2 level control experiments.*

Control of the liquid level in the lower tank is more challenging due to the higher $\frac{L_p}{T_p}$ ratio and second order process dynamics when compared to tank 1. For this, students can explore PID control for setpoint tracking using the Ziegler Nichols ultimate cycle tuning rules given in Table 2 and evaluate the difference in control response when the control algorithm in (8) is implemented.

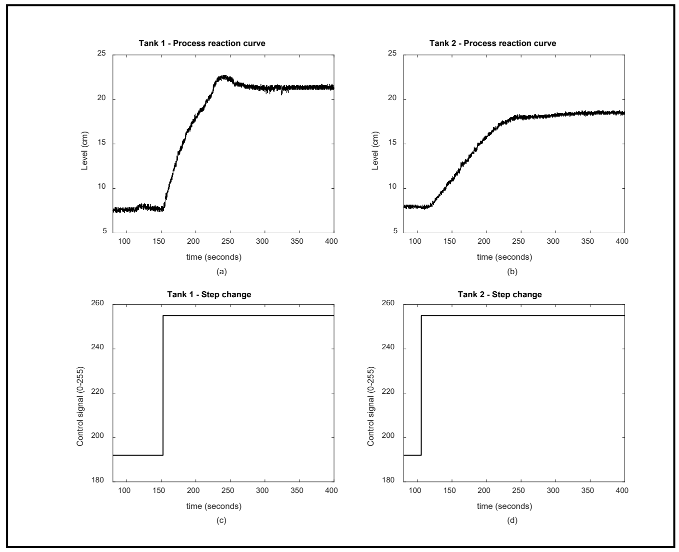

Fig. 6. Process reaction responses for Tank 1 (a) and Tank 2 (b).

D. *Discussion of the experimental results.*

Fig. 7 shows the responses obtained using P, PI and PID controllers in the upper tank. With pure P control, the level tracks the setpoint with considerable offset. This is expected since there is no corrective action provided by an integral term in the presence of a constant error. An improved closed loop response is obtained using the PI control. There is however noticeable overshoots and undershoots present when the level setpoint is changed. This is due to the Ziegler Nichols tuning rules, which is known to produce oscillatory responses due to the quarter wave damping response which it is based on. The PID control produces a similar response, albeit the control signal suffers from a considerable large variation due to process noise. This effect could lead to premature failure of the final control element due to wear and tear caused by the erratic motion. Disturbance rejection properties of the control system is shown in Fig. 8. The PI controller is capable of responding to a sudden variation in level and recover within a short period. Fig. 9(a) shows the PID response in the lower tank. The system response is significantly improved by using the derivative filter as shown in Fig. 9(b).

V. Conclusion

Using the experimental didactic level control system, it was possible to gain a better understanding of process dynamics, controller functions and parameter selection. The control of liquid level in the upper and lower tanks was carried out easily by designing and deploying the control system in real time using MATLAB™ and the ARDUINO® microcontroller. The efficacy of the system is evident in the closed loop responses that are obtained in real time. In future works, the system can be expanded to introduce advanced control concepts such as FL and ANN control schemes. Currently, the hardware system is only accessible from the university control system laboratory. It will be highly beneficial to have remote access to the training hardware using a secure local area network connection.

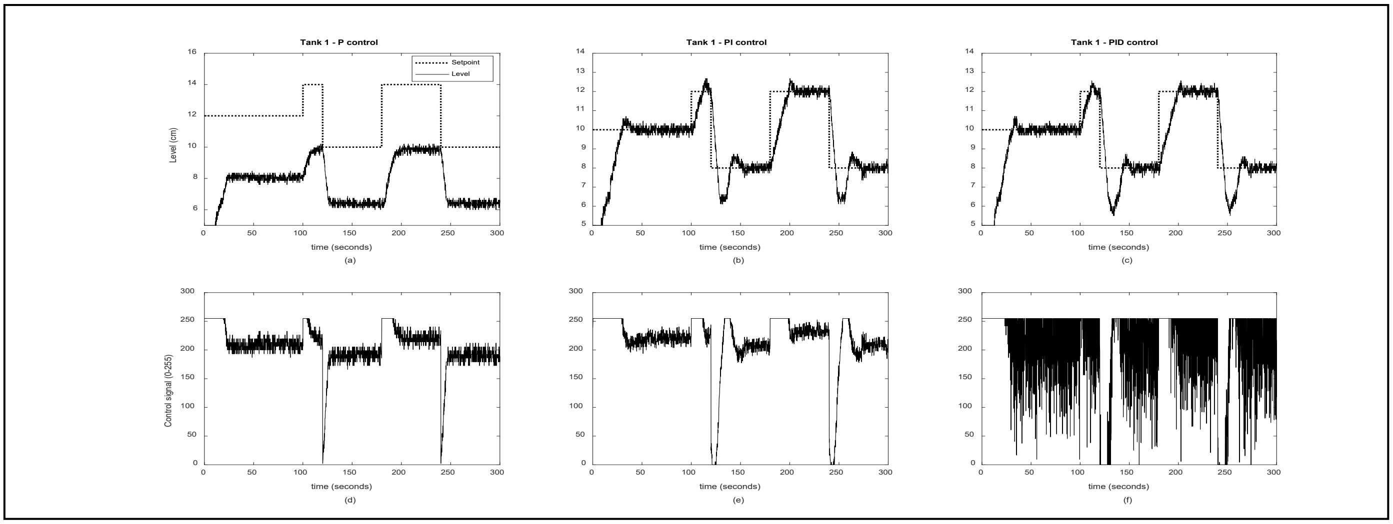

Fig. 7. P (a), PI (b) and PID (c) control of the level in Tank 1.

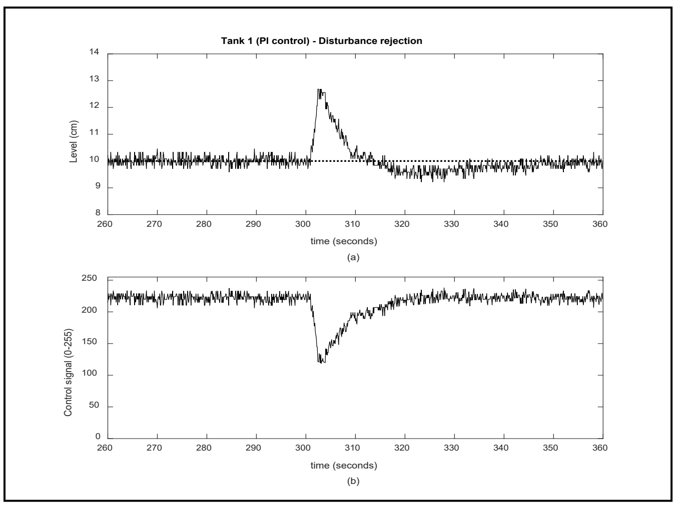

Fig. 8. Disturbance rejection response for Tank 1.

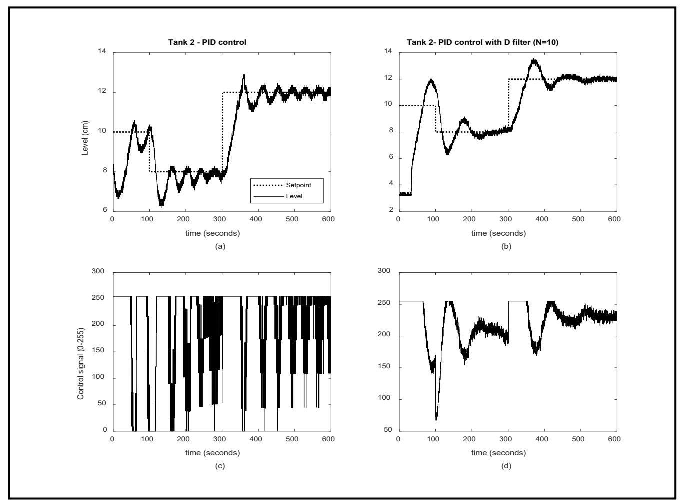

Fig. 9. Tank 2 PID control without D filter (a) and PID with D filter (b).

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