Realization of Real-Time Hardware-in-the-Loop for a Liquid Level with Open-loop Ziegler Nichols Technique

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Abstract – *This paper presents the realization of a real-time hardware-in-the-loop (HIL) for a liquid level control system. Multifarious controllers that were proposed in the previous literature are constrained within simulation platform. Several advanced control configurations are implemented in the hard-wire platform that incurs complex programming and requires computational burden. These kind of control configurations do not permit the operator to tune the control parameter online. Moreover, the parameters inside the microcontroller are unobservable to the operators. As such, the need to implement a real-time HIL for a liquid level control system worthwhile to the operators. It gives intuitive configuration and user-friendly application to the operators because the tuning process can be implemented in didactic manner. Furthermore, the controller design phase can be conducted with lees programming burden. Implementing the HIL requires three phases. The tank must be calibrated to obtain a linear relationship between the voltage and the water level. Afterward, the open-loop Ziegler Nichols is exploited to tune the parameters of three term Proportional-Integral-Derivative controller. The controller is then implemented in the MATLAB SIMULINK platform in the host computer. The result shows that the proposed real-time configuration guarantees the asymptotic tracking of the demanded water level with only* 1.247% *steady state error.*

Keywords: *Control system, Ziegler Nichols, PID; Water level*

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I. Introduction

Liquid level control systems are vital in chemical process industries [1], [2], manufacturing assembly line, automotive sectors [3], [4], [5] and food manufacturing processes [6]. The system works by pumping water or liquid into the tanks, storing the water in them and then pumping again to another tank for a certain appropriate level. In control engineering point of view, level control in the tank can be done by manipulating the liquid flow rate such that the appropriate level of the liquid set point can be obtained. For some multi-tank systems, the tank either behaves as a buffer tank or working tank.

Several advanced control configurations for level system were implemented in the hard-wire platform that incurs complex programming and requires computational burden. Often, the tuning process of the controlled tank systems is done prior before the system running. Plus, the tuning processes are done separately where the parameters inside the microcontroller are unobservable to the operators. As such, to have a real-time perceptibility to the liquid level in process industries is a must.

To date, researchers and engineers proposed multifarious controllers or algorithms for a liquid level control system. Nevertheless, the proposed algorithms are tested in simulation platform where the efficacy of the algorithms in real-time control system can be disputed. For instance, three-term Proportional Integral Derivative (PID) controllers are widely proposed in the simulation of liquid level systems [7]. In the simulation platform, the appearance of nonlinearities and exogenous perturbation can be easily corrupted in order to achieve predefined control objectives. In practice, these nonlinearities cum perturbations appeared with some degree of control acceptability. As such, it is quite often that the proposed algorithm works well in simulation platform but suffers from performance detraction when being applied to the real process.

Several attempts have been made to improve PID controller. In [8], weird oscillation of two-term Proportional Integral (PI) has been diminished by using St. Clair method. However, the proposed remedy has been tested in simulation platform only. In [9], [10], a Model Reference Adaptive Controller (MRAC) is used to improve PID performance. The complexity of MRAC technique denies the applicability of such controllers to be realized in practice. More recently, PID performance has been claimed for improvement by augmenting an advanced control technique. For instance, fuzzy logic control [11], particle swarm optimization [12] and model predictive control [13] have been exploited to improve PID performance in liquid level systems. Though these controllers are bounded within simulation platform, pondering to implement them in real time control system would require complex design and thus, demanding high speed processor. Moreover, some advanced nonlinear control techniques such as back-stepping [14] [15], or Lyapunov-based design [16] are not necessary to this extend.

Thus, this paper proposes the realization of PID controller in the hardware-in-the-loop (HIL) facility for a liquid level control system. An *ATmega328P* microcontroller is used to interface the tank system to the host computer. The PID algorithm is designed by the Open-loop Ziegler Nichols method. The algorithm is then developed in the SIMULINK via MATLAB platform in the host computer to facilitate real time control configuration.

II. Methodology

The methodology to reach main results consists of 3 phases. In the first phase, the experiment is conducted to calibrate the tank at hand. Then, an Open-loop Ziegler Nichols tuning approach is conducted in the second phase. In the third phase, the PID parameters obtained from the Open-loop Ziegler Nichols tuning is then realized in the SIMULINK platform where the HIL configuration is set up by using *ATmega328P* microcontroller and the host computer.

A. Tank Calibration

The system under studies is a single tank *CTS-001* apparatus. The block diagram of a single tank system is shown in Fig. 1. Note that, U_{in} denotes the input voltage to the pump. Q represents the water flow rate controlled by the pump. H represents the level of the water in the tank (in *centimeter*). Whereas U_{out} denotes the output voltage that can be measured through the capacitive type level sensor. Experiment must be conducted to calibrate the pump and sensor in order to achieve the precise relationship between the height and voltage (*volt-centimeter)*.

Beforehand, let the system in Fig. 1 to be lumped in a single system as shown in Fig. 2, and be represented by linear expression $v(h)$ relating the voltage v and the level of the water h.

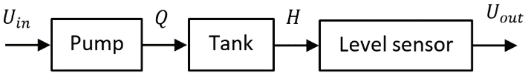

Fig. 1. Single tank system under studies

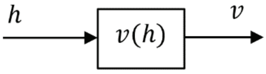

Fig. 2. Relationship between voltage and level

The level of the water in the tank is measured by the capacitive type level sensor that changes the capacitance with respect to the level changes. Via signal conditioning, the capacitance is converted to a DC voltage ranging from *0V* to *5V*. The calibration output is tabulated in Table 1. The v/h-relationship can be obtained by plotting the calibration data in Fig. 3.

TABLE I
CALIBRATION DATA FOR THE TANK SYSTEM

Level of Water (cm)	Output Voltage (V)			Average Reading of Output Voltage (V)
	Reading 1	Reading 2	Reading 3	
5	0.717	0.661	0.665	0.681
10	1.807	1.561	1.542	1.637
15	2.651	2.686	2.625	2.654
20	3.366	3.386	3.359	3.370
25	4.021	4.075	4.100	4.065

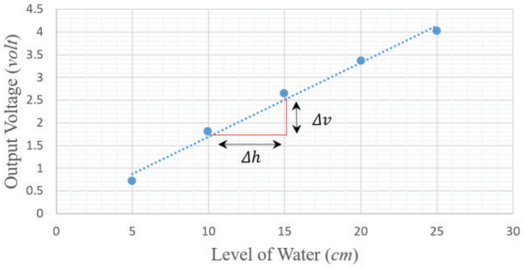

Fig. 3. Plot of voltage and level

Then, the v/h-linear expression can be computed by observing the slop $m = \frac{\Delta V}{\Delta V} = 0.1633\, v/cm$ and the voltage intercept $c = 0.0623V$. Therefore, the v/h-linear expression can be obtained as in equation (1).

$$v(h) = 0.1633v + 0.0623 \tag{1}$$

Equation (1) can be realized in the Simulink platform in the host computer. The model is depicted in Fig. 4.

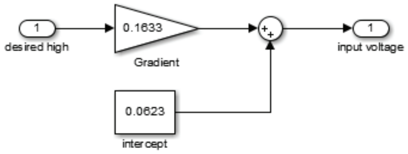

Fig. 4. v/h-linear expression in the host computer

With the model in Fig. 4, any desired level inputted by the operators will be converted into electrical voltage ranging from *0V* to *5V*. This is the allowable voltage range accepted by the *TTL*-based *ATmega328P* microcontroller that behaves as a communication interface as well as the program compiler relating the tank to the host computer.

B. Open-loop Ziegler Nichols Tuning

In this phase, PID parameters are designed to guarantee the asymptotic tracking of the output level. The PID algorithm can be expressed as

$$G_{PID}(s) = K_p\left(1 + \frac{1}{T_I s} + T_D s\right) \tag{2}$$

where K_p denotes a proportional gain, T_I represents the integral time constant, and T_D represents the derivative time constant. There are many methods available in literature. This study utilizes an Open-loop Ziegler Nichols or a process reaction curve method for several advantages. Open-loop Ziegler Nichols method does not require a mathematical model of the system at hand. Thus, the input-output relationship due to unit step is a must. Beforehand, the tank system is open-looped. Hence, unit step input is applied to the tank system. The time taken by the pump to fill up the tank is recorded and is tabulated in Table II.

TABLE II
TIME VERSUS WATER LEVEL

Time (s)	**Level of Water (cm)**
0	0.0
5	1.7
10	6.5
15	11.6
20	18.5
25	21.7
30	25.5
35	29.0
40	30.0
45	30.0
50	30.0
55	30.0
60	30.0

Data in Table II can be realized in the reaction curve indicated by Fig. 5. Through the maximum gradient, the equivalent dead time (L) and the equivalent time constant (T) were obtained. The value of L is observed as $0.625\ sec$ and T is $38\ sec$. Hence, under 25% damping criteria (or quarter amplitude), the parameters for PID controller can be calculated via look-up table in Table III.

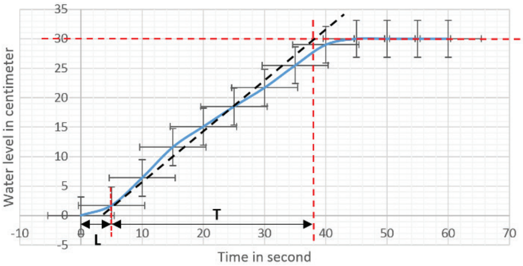

Fig. 5. Reaction curve for open-loop Ziegler Nichols method

TABLE III
OPEN-LOOP ZIEGLER NICHOLS TUNING TABLE

Controller	Parameter		
	K_p	T_i	T_d
P	$\frac{T}{L}$	∞	0
PI	$0.9\,\frac{T}{L}$	$\frac{L}{0.3}$	0
PID	$1.2\,\frac{T}{L}$	2L	0.5L

As such, the numerical PID algorithm can be computed as

$$G_{PID}(s) = 60.8 + \frac{48.64}{s} + 19s \tag{3}$$

C. System Configurations

Overall system configuration for HIL tank system is depicted in Fig. 6. PID algorithm in equation (3) is embedded in the *ATmega328P* microcontroller circuitry via MATLAB SIMULINK model in the host computer. This method relaxes the need for complex programming and avoid computational burden incurred by the host computer. The *ATmega328P* microcontroller controls the flow rate of the inlet water by controlling the duty cycle of the pulse width modulation (PWM) signal. The capacitive level sensor sends the measured level in volts (ranging from $0V - 5V$) to the *ATmega328P* microcontroller circuitry. The specification for the *ATmega328P* microcontroller circuitry is tabulated in Table IV.

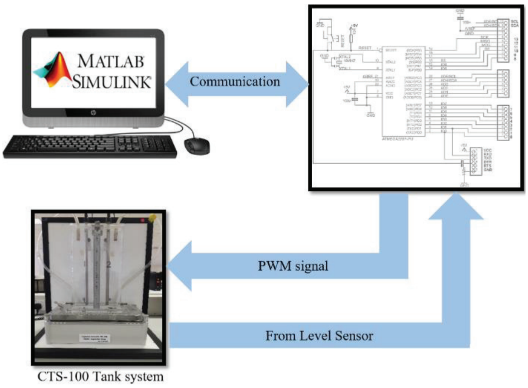

Fig. 6. System configuration for HIL tank system

TABLE IV
SPECIFICATIONS FOR ATMEGA328P CIRCUITRY

ATmega328P circuitry	Specifications
Operating Voltage	5V
Input Voltage	7-12V
Input Voltage (limit)	6-20V
Digital I/O Pins	14
PWM Digital I/O Pins	6
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz

III. Result

In this section, the effectiveness of the PID algorithm in equation (3) is tested in a real-time frame. The efficacy of the PID algorithm is verified by injecting the demanded $15\ cm$ water level. This demand input can be set in the host computer via MATLAB SIMULINK platform.

A. Tracking performance

Fig. 7 shows the tracking history of the water level. With demanded $15\ cm$ water level, visual observation guarantees the asymptotic tracking of the water level. The oscillation comes from the water gushing generated by the pump. This effect can be reduced by reducing the pump flow rate. This can be implemented in the host computer where the operator can reduce the duty cycle of the PWM signal to the pump. However, this condition increases the settling time as tradeoff. From Fig. 7, it is observed that the control system requires around 1.4 seconds to reach $15\ cm$ level.

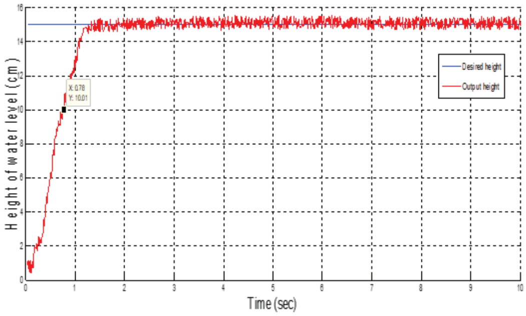

Fig. 7. Tracking performance for $15\ cm$ demanded level.

B. Steady state

Due to small oscillation in the output level, the steady state error e_{ss} can be computed by considering the average output level

$$e_{ss} = |h_{demand} - h_{average}| \tag{4}$$

where the average output level is computed as

$$h_{average} = \frac{1}{N} \sum_{t=e_{ss}}^{N} h(t) \tag{5}$$

with N is the number of recorded data. As $h_{average} = 15.2021\ cm$, the steady state error can be computed as

$$\begin{aligned} e_{ss} &= |15 - 15.2721|\ cm \\ &= 0.2021\ cm \end{aligned} \tag{6}$$

Thus, the percentage of error can be recorded as 1.247%.

IV. Conclusion

Though this research does not open up new avenue to the advanced control technique, the proposed HIL overcomes the shortcoming of conventional level control systems. The proposed HIL offers simple design and relaxes programming complexity. The proposed HIL also simplifies the online tuning process. The result promises asymptotic tracking of the water level with less steady-state error and with acceptable settling time. The use of MATLAB SIMULINK also relaxes the need to develop a customized graphical user interface.

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