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Low Cost Test Bed for Implementation of Proportional-Integral-Derivative Control

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Abstract:

There are limited test beds to emulate real industrial controls in academic environment especially, in developing countries. This is as a result of high procurement and maintenance costs of such testbeds. Most times, what is obtainable in academic environments is on-off control with relay output system. In industries where precision in product quality is required, on-off control is not normally desired. Rather, complex control that encapsulates proportional, integral and derivative algorithm or its variant is normally required. A fast response system would normally require Proportional-Integral (PI) - control while a slow response system will require Proportional Integral Derivative (PID) control. This work developed a PID control test bed leveraging on Arduino IDE embedded resources while using triac as actuator and thermistor as feedback element integrating Atmega 328 interfaced to a computer as target controller element. Experimental method was used to determine the tuning parameters of the PID controller leveraging on the system's oscillatory data. A Prototype Process Plant (PPP) emulating the temperature control of acid gas removal from natural gas was used to demonstrate how the test bed works. With 98.75% accuracy as the minimum benchmark with respect to the considered PPP plant, result showed that the designed testbed has an acceptable accuracy of 99.85 % while maintaining system's availability and integrity.

Keywords: PID control, feedback element, cost effective, oscillatory data, test bed, Arduino IDE embedded resources.

I. INTRODUCTION

A typical control system functions generally to actualize the control objective of the system within the shortest possible time (Bela, 2006). This control system which is the bed rock of automation in industries can be categorized into open loop and close loop control system (Bela, 2006). . While open loop control system which is time dependent is not widely used both in home and industry automation due to its limitations, the closed loop also called feedback control system has gained universal acceptance in the world of automation (ISA, 2009). Control engineers design control systems, and for optimal performance to be achieved, the designer must be grounded in fundamental concepts of control system. It is expected that university education should offer engineering students these fundamental understanding of control systems. It is however sad to note that control courses in the universities especially those in the developing nations of the world suffer setbacks. One of such setbacks is lack of well-trained control experts needed to communicate control system concepts to the students (Chen & Abu-Nimeh, 2011). Another one is high cost of control system test bed needed to demonstrate industrial control system principles to the students. The effect is that there are few institutions offering control or automation courses in these developing nations, yet automation is the basic building block of production machines in industries be it pharmaceutical, automobile, oil and gas or robotic industries. Proportional-Derivative-Integral (PID) algorithm is a fundamental algorithm used in most industrial feedback control system. This work developed a low cost testbed for classroom implementation of PID algorithm. Section II reviewed PID algorithm, and test beds used in implementation of control system while section III presented the high level description of the test bed. The schematic design of the test bed was done in section IV before implementing it in V. The result is shown and discussed in VI while bill of engineering measurement and evaluation is presented in VII before concluding the work in VIII.

II. REVIEW OF PID ALGORITHM AND TEST BEDS FOR IMPLEMENTING CONTROL SYSTEM

A. Review of PID Algorithm

PID algorithm whose first theoretical analysis dates back to 1922 (Dale & Stephen, 2009) is a backend algorithm which has been universally accepted in industrial automation. It is made up of three basic components as shown in equation (1): the proportional, derivative and integral components (Anthony, 2014).

$$m = K_p e(t)_{(t)} K_i \int e(t)\, dt + K_d \frac{de(t)}{dt} \qquad (1)$$

The proportional component deals with the present error in control system while the integral and derivative components deal with past and future errors respectively (Anthony, 2014). Figure 1 is a typical feedback control loop where PID algorithm can be deployed.

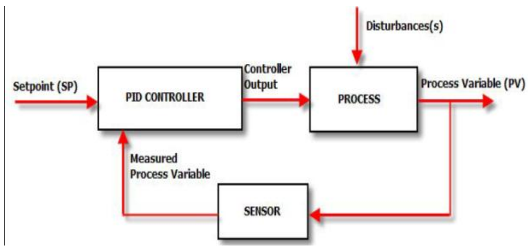

Figure 1: typical feedback control loop (Anthony, 2014)

The set point SP, is the control objective which the controller works to actualize by measuring the process variable through a sensor, and then invoking pid algorithm after calculating the error variable, e according to equation (2), where b is the feedback signal (Anthony, 2014)

$$e = S - b \qquad (2)$$

Figure 2 is pictorial representation of how PID control loop works.

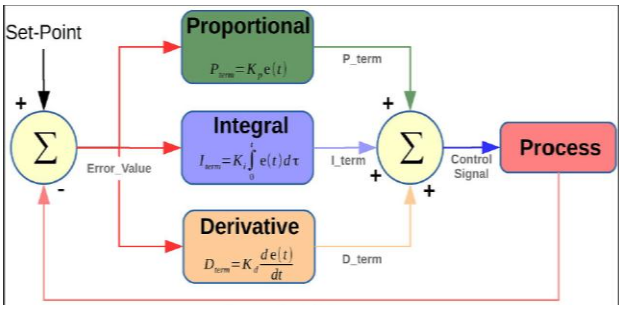

Figure 2: Pictorial representation of PID loop (Anthony, 2014)

PID algorithm has a number of advantages. Every form of control system revolves around this equation be it robust control, fault tolerant control, on-off control, feedback control as well as feed forward control. It was primarily designed to control systems whose transfer functions are not known in details. Essentially, it is used to control processes without first of all determining the transfer function or mathematical models of the process.

B. Review of Testbeds for Implementing Control System

A number of attempts have been made to build testbeds for implementation of control system concepts. The authors of (Haihui, et al., 2013) worked on the design of industrial control system (ICS) testbed that is based on emulation and simulation of SCADA control system. In their approach, control system components were used to develop a virtual platform for experimenting control system security principles. Although (Haihui, et al., 2013) specified some control system components like actuator, sensors and processors, it was not specifically directed to PID control principles. (Michele, et al., 2010) carried out preliminary study of a wireless process control network using emulation testbed. The testbed was used to investigate the risks that operators of control system might face while installing Wi-Fi access technologies within a process control network. While (Michele, et al., 2010) is very good for training control system operators in system upgrading, it does not deal with understanding of control system principles. The work done by (Hannes, et al., 2015) recommended some tools and components for effective design and implementation of control system testbeds. These include networking components like routers and switches, dedicated human machines interfaces, proprietary soft wares like LabVIEW and Matlab. These tools and components are so expensive that an average student in a developing country cannot afford them. Even some institutions in such countries may not want to buy them as a result of various needs competing for their scarce resources. This work used components that are available in local market to design and implement a testbed for implementing PID control system. The test bed can be owned by a student since the cost is less than a hundred US dollar.

III. DESCRIPTION OF THE TEST BED FOR IMPLEMENTING PID ALGORITHM

Figure 3 shows the block diagram of the testbed proposed in this work for implementation of PID algorithm. Below is brief description of each block that makes up the block diagram.

Computer: this is the laptop or desktop computer that contains the user interface (UI) that is used to monitor and control the process plant. The front end parameters of the process plant, namely the set point Sp, of the process plant, Kp, Ki, and Kd of the PID controller are all available to the operator via the UI. The operator can change the values of these front end parameters at will.

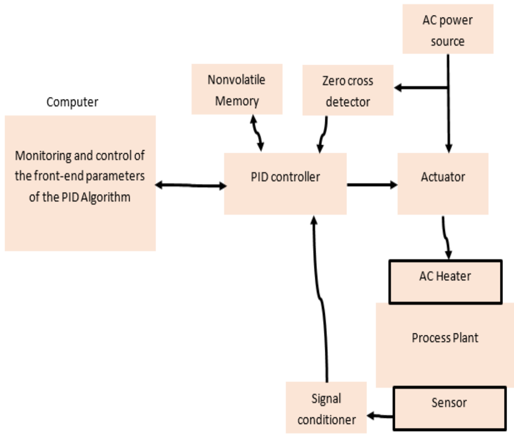

Figure 3: Block diagram of the proposed testbed for PID implementation

PID Controller: this is the controller that contains the PID algorithm. It coordinates the activities of the entire system. It computes the algorithm and sends the output to the actuator at a time that synchronizes with the zero crossing of ac signal to the actuator.

The controller also stores and retrieves the initial values of the process parameters to and fro the nonvolatile memory besides sending reports to the operator via UI. Finally, the controller also gets the feedback signal from the sensor attached to the process plant.

In this work, Arduino Leonardo device is used as a controller due to the following reasons (ArduinoGroup, 2017).

- It has internal 10 bit analog to digital converter (ADC) with six channels.
- It has 32 KB memory with on-board 1 KB of EEPROM.
- It has USB connectivity, so data communication between the controller and computer is easy.

Arduino comes with IDE that has in-built serial monitor. So one can easily develop a UI using the serial monitor.

Nonvolatile Memory: this is used to store the initial process parameters (Sp, Kp, Ki and Kd) of the process plant. The

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minimum and maximum values of these parameters are also stored here, never to be over written or erased even when power goes off. The on board EEPROM of the controller was used for this purpose.

Actuator: this switches the ac heater on in proportion to the signal received from the controller. Triac is used in this work as it makes for proportional, smooth and noiseless switching.

Zero Cross Detector: Triac requires proper timing for smooth switching. So, zero cross detector is used to alert the controller when the ac signal crosses zero point. Opto coupler is used for this purpose.

AC Heater: this is used to heat up the environment of the process plant. AC incandescent bulb was used for this purpose.

The Process Plant: This contains the substance whose physical property is under control. A cuboid of 25cm is used as a process plant, and the property under control is the temperature of the enclosed air. Sensor is attached to process plant. Thermistor is used as temperature sensor because of its availability in local market. Signal conditioner for the sensor signal is the internal ADC of the controller.

IV. THE SCHEMATIC DESIGN OF THE TEST BED

Figure 4 shows the schematic design of the test bed.

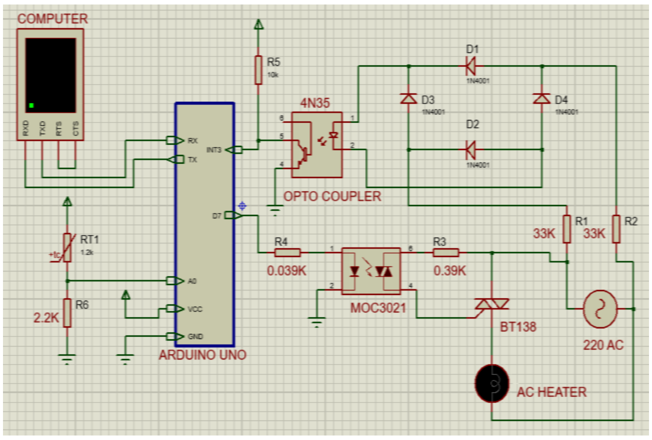

Figure 4: Schematic design for implementation of PID Algorithm

There are three inputs to the controller: the computer, opto coupler and sensor inputs. The outputs from the controller are serial output Tx, to the computer, and the PID output D7 to the triac driver moc3021. Brief descriptions of the major components of the design as well as the reasons for choosing component values are given below.

The Bridge Rectifier Circuit and Opto Coupler: Triac works effectively when switched at zero crossing of ac signal. So there is need for the controller to know when the ac signal crosses the zero point so that the triac can be fired appropriately. But the controller works with 5V dc, so there is need to isolate the ac signal from the controller. This is what the opto coupler, 4N35 does. Opto coupler has internal light emitting diode, LED which biases its internal transistor optically each time there is a positive going signal from anode to the cathode of the coupler as shown in figure 4. It then means that a full wave rectifier is required for complete detection of zero crossing points of the ac signal. The full wave rectification is achieved by arrangement of four diodes 1N4001 as shown in figure 4. Now the opto coupler requires at least 6mA to be biased (Fairchild, 2017), and the peak repetitive reverse voltage of the diode 1N4001 is 50V (BKC, 2017) . So out of the 220V ac from normal public ac supply, 170V (220-50) needs to drop across a resistor. From Ohms law, the value of resistor that will drop a voltage of 170V with series current of 6mA is 28.333kΩ. The standard value of resistor that is close to this value is 33kΩ. So in figure 4, $R1 = R2 = 33\text{k}\Omega$..

The Triac BT138 and Its Driver Moc3021: the PID output is analog signal. So to have a proportional switching effect on the load, the ac heater, there is need for ac actuator whose output can be controlled based on its input signal. Triac is well suited for this purpose, and it requires a driver since the signal from the controller cannot drive it directly, hence moc3021. Now, PID control can be applied even when the transfer function of a system is unknown (Abdel-geliel, et al., 2014). So in this case, it is not absolutely necessary to know the transfer function of the process plant. However, it necessary to choose an actuator that will be able to handle the maximum current that will ever be envisaged in the system. The triac, BT138 has a maximum on-state current of 16 amperes with repetitive peak off-state voltage of 600V (Philips, 2018). It then means that for a resistive load, the maximum load that can be driven through the triac at 220V ac is $220x16 = 3520W$. The heater used in this work is 120W ac incandescent bulb. This is far below 3520W. The triac driver moc3021 is instrumental to the switching of the load (heater). High current surge can break down the driver. So, resistor R4 is used to protect the driver from high current surge. The maximum rated current surge is 1.2A (Texas, 2018). With R3= 390Ω , the driver can withstand a voltage surge of 460V ac. The LED trigger current of moc3021 is 15mA (Texas, 2018). So with a resistor $R4 = 39\Omega$, a pid output of 0.6v will be able to fire the triac.

V. SYSTEM IMPLEMENTATION

Figure 5 shows the hardware implementation of the test bed.

Figure 5: Hardware implementation of PID testbed

System components were bought from local market while the printed circuit board design of figure 4 was done using proteus software. PID algorithm of equations (1) and (2) were implemented using embedded c language, a hybrid of assembly, C and C++ languages in Arduino integrated development environment (IDE). The sample codes are shown in figure 6.

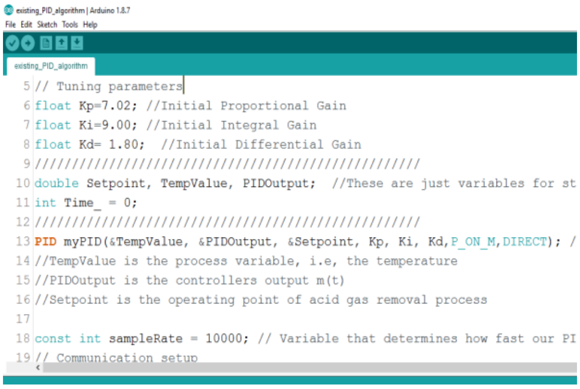

Figure 6: Implementation of PID Algorithm in Arduino IDE

The K parameters of the process plant were determined using oscillatory method (Schneider, 2017). The process parameters determined are K_p, K_i, K_d = 7.02, 9.00 and 1.80 respectively as shown in figure 6. The complied codes were uploaded to the Arduino board via a serial cable. The process plant was used to emulate the temperature control of acid gas removal from natural gas. The full description of process of acid gas removal from natural gas is given in (Stuart, 2000), (Companies, 2015)(Shell, 2015), and (Mbonu, 2017). A total of 300 readings were collected at interval of three seconds from the process plant while emulating the temperature control of acid gas removal from natural gas at optimal temperature of 40 ° C with minimum and maximum temperatures of 38 ° C and 43 ° C respectively. Figure 7 shows the sample of collected data.

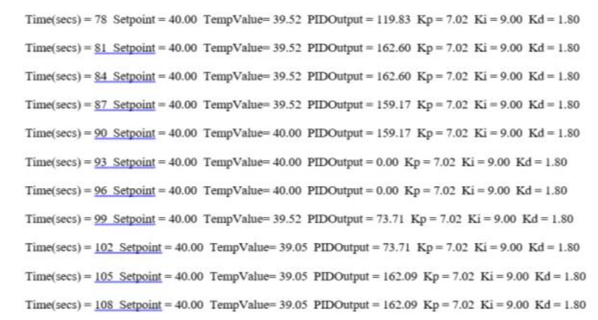

Figure 7: Sample of data collected from process plant

VI. RESULT AND DISCUSSION

A. Result

Figure 8 shows the process plant's response to PID algorithm.

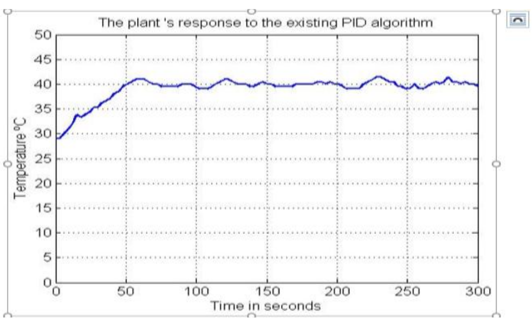

Figure 8: Response of the test bed to PID algorithm

B. Discussion on performance of the testbed

From figure 8, it is seen that the designed PID test bed was able to achieve the control objective of maintaining the temperature of the process plant within the temperature range of 38 ° C and 43 ° C with 40 ° C as the optimal or ideal performance. The mean steady state error (MSSE) of the test bed considering the 27th to 101th temperature data is 0.062631579 which is approximately 0.06. It means the accuracy of the test bed is $((40 - 0.06)/40) * 100 = 99.85$ %. This showed that the test bed control performance is acceptable since the minimum control accuracy required to achieve the control objective in the considered process plant is $((40 - (3\text{-}2)/2)/40) * 100 = 98.75$ %.

VII. BILL OF ENGINEERING MEASUREMENT AND EVALUATION.

Table 1 shows the implementation cost of the test bed. The cost is about 60 US dollars. This is almost nothing when compared with the cost of other control system test beds (Haihui et al., 2013). Students can buy this test bed for personal learning of PID control principles.

Table 1: Cost analysis of the test bed

s/n	Components	Quantity	Unit Price (#)	Amount (#)
1	Arduino Board	1	4000.00	4000.00
2	Moc3021	1	200.00	200.00
3	BT138	1	100.00	100.00
4	4N35	1	100.00	100.00
5	33k resistor	2	10.00	20.00
6	120w bulb	1	100.00	100.00
7	Thermistor	1	100.00	100.00
8	39 ohm resistor	1	10.00	10.00
9	10k Resistor	1	10.00	10.00
11	Process Plant	1	10000.00	10000.00
12	1N4001	4	20.00	80.00
13	Transportation			2000.00
14	PCB and Packaging			5000.00
Total Amount				21,720

VIII. CONCLUSION

A low cost test bed for implementation of PID algorithm was designed and implemented in this work. This test bed can be used to emulate the temperature control of acid gas removal from natural gas in laboratory while learning the basic principle of PID feedback control system.

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