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1. Abstract

The water level control laboratory aimed to explore the use of PID controllers in closed-loop feedback systems as well as analysing the functionality of open-loop systems. This was achieved through the calculation and estimation of the open loop response alongside the analysis of multiple of PID systems - measuring the response off each set of PID constants. The findings suggest that feedback systems are more effective than open-loop systems in terms of rise-time and settling-time. PID controllers are key to system optimisation and can be detrimental if not set correctly. Overall, this laboratory provides important insights into the EMS507 module.

2. Introduction

The water level control laboratory provided practical insights into controller theory and complemented the theoretical knowledge gained in the EMS507 module. The experiment was centred around the control of the water level within a water tank – making use of both an open and closed loop system. The laboratory experiment aimed to achieve the following objectives: designing a PID controller using *MATLAB* and verifying it through practical procedures, gaining hands-on experience in building real-time control systems, tuning PID systems, and analysing experimental results. This report outlines the experimental procedures and results in addition to presenting an analysis of the findings in accordance with the stated objectives.

2.1 Control Theory

The field of control theory can be defined as the engineering and mathematics concerned with the analysis and design of controllable systems. Specifically, controller theory encapsulates behaviour modelling alongside controller design and stability analysis of systems with the goal to create systems that behave in a desired way - even in the presence of external disturbances or uncertainties. When being applied, controller theory can either act as a closed or open system – each following a different method of system control.

The concept of control theory when applied to closed -loop systems cover the use of feedback to influence the behaviour of the system in order to achieve a desired goal. (Univerity of Waterloo, 2021). In practice, a closed loop system makes use of sensors to compare the system output against a desired output subsequently adjusting using actuators – getting closer to the optimal output with each system iteration or loop.

Open loops, described as 'systems that employ no analysis sensors and rely on calibrator actuator setting to achieve desired action' (Rob Tulson, 2012), are essentially set and go systems which do not rely on any feedback to operate – instead only requiring an input. This type of system is inherently simple when compared to closed systems since they do not aim to rectify their outputs based on sensory response, meaning that any input for the system must be optimised prior to use.

3. Experimental Procedure

The experimental procedure section of this report covers the steps taken within the laboratory to complete research objectives as stated. It encompasses a detailed account of the apparatus and preparatory measures that were necessary to conduct the experiments. Additionally, this section describes the design and implementation of the PID controller alongside a detailed account of both the open and closed loop procedures.

3.1 Apparatus

The water-level control laboratory was conducted using a process flow circuit, and CE117 mimic panel in tandem with a controller software 'CE200'. Together, this apparatus allowed for the completion of both tests – including the adjustment of PID coefficient values in the second procedure.

The process flow circuit allowed for the flow of water into the process vessel from the reservoir using a controllable pump. In addition, the flow rate of the water is measured via a flow transmitter in series between the pump and tank. While the water was in the process vessel, a level transmitted (LT) measures the hight of the liquid – this provides feedback to the system in the case that it is being used. To remove water from the vessel, a drain valve opens – emptying the water back into the reservoir. This means that the total volume of water in the system is constant and not influenced by outside sources. The pump, and hence flow rate, are controlled by the external voltage through the control module.

To allow instructions from the controller software to be interpreted by the controllable components, a CE117 control module is used – acting as an interface. The front panel of the control module provides the means to physically access the inputs and outputs of the transmitters and actuators of the CE117.

The controllable pump valves, as previously mentioned, can be manipulated using the CE200 controller software. The constants found during the construction of the PID controller can be input to the controller software. As well as this, the controller software records and outputs experimental results values for later analysis.

3.2 PID Controller Design

The design of the PID controller was conducted prior to the laboratory experiment. Using the software *MATLAB*, a simulated steady state response on a closed-loop system could be analysed. This meant it was possible to optimise the proportionality, integral and differential constants for the PID controller prior to the lab.

To determine the better steady state response, a simulated system could be modelled using the given transfer function and time constant equation alongside the input flow unit conversion equation, $G(s) = \frac{K}{s+1/\tau}$, $\tau = \frac{\Delta V}{\Delta F_{in}}$ and $K = \frac{1}{60}$ respectively. Using these equations, a step response graph of amplitude against time in sections can be modelled based on a PID inputs. This demonstrated the time taken for the system to settle. An ideal PID controller would create a graph with a low max peak, low settling time and be stable.

Using this method in conjunction with the initial PID constant values, the following sets of PID constants were found – all shown in tabulated form below.

Value set	k_P	k_I	k_D
Initial	10	0.5	0
1	40	0.5	0
2	10	0.5	1
3	10	0.1	0

3.3 Open-loop Procedure
The procedure for the open-loop step level response test aimed to make the user familiar with the process vessel as well as allow for a time constant to be found. Prior to beginning the experiment, the process vessel must be fully emptied with the drain valve and air vent remaining open. To begin the first measurement case, set the pump voltage to 4V and the valve to 10V; when the water level comes to rest, slowly increase the voltage until it is just above the heat exchanger and record the height of the water level (this is level A). Repeat this for the second measurement case, increasing the pump voltage by 0.5V (this is level B).

3.4 Closed-loop Procedure
The procedure for the closed-loop control by pump speed test aimed to control the level in the process vessel using the PID controller. Prior to beginning the experiment, the process vessel must be fully emptied with the drain valve and air vent remaining open. To begin testing the initial PID controller, input the constant values and adjust the setpoint to 6V with the value voltage at 10V. Subsequently, increase the setpoint by 0.5 and use the software to monitor the level until it is stable. Reset and repeat this process with the each set of constant values found prior to the lab.

4. Results & Calculation

Through the completion of the water level control experiments, the response of both open and closed loop systems was observed. This was done through measurement of the time constant within the open loop procedure and through measurement of the water level over time in the case of procedure 2.

4.1 Open-loop
The objectives of the open-loop laboratory required the time constant to be found using both estimation and calculation – as well as determining the difference between the two values.

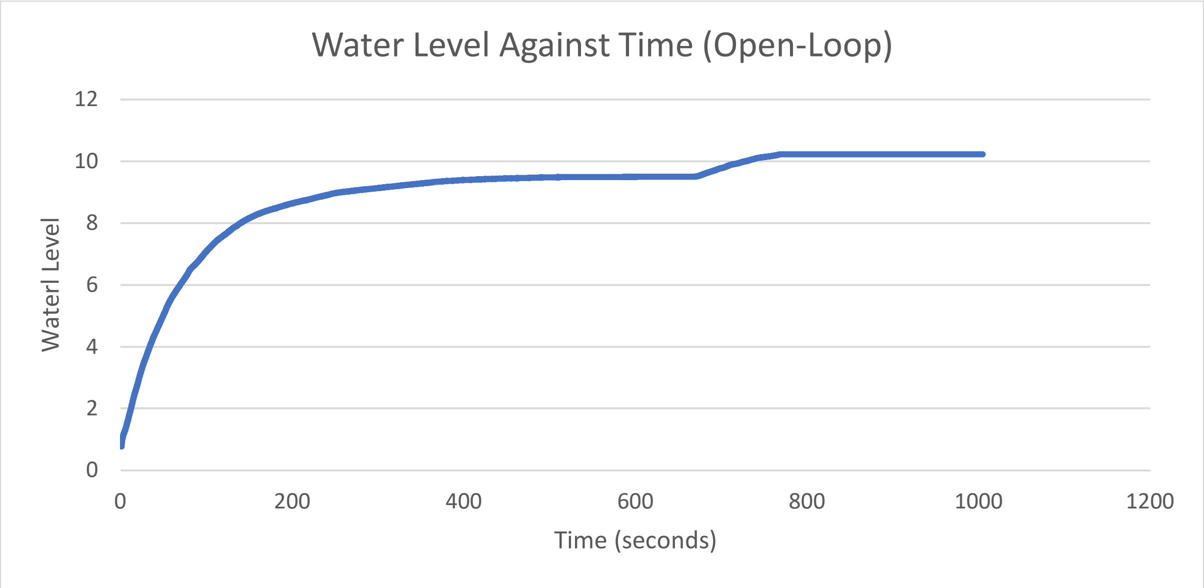
First, the estimated time constant if found; the estimated time constant is equal to 62.3% of the time taken to go from water level A to water level B.

The calculation of the time constant required the use of multiple simple equations. Initially, the flow rate in volts must be converted to meters cubed per second. 1 volt is equal to 1 litre per minute which in part is equal to 1.6667E-5 meters cubed per second. Taking the 4.5-volt flow rate case, the converted flow rate is 7.5E-5 meters cubed per second. Next the change in flow rate between the levels must be calculated for use in the equation $R = \frac{change\ in\ flow\ rate}{chang\ \ in\ height}$. Using experimental values, the equation can be substituted as $\frac{0.19-0.15}{(8.333E-5)-(7.5E-5)}$ giving R as 4800. Subsequently, the internal area the process vessel (S) must be calculated. Since the internal diameter of the vessel is 150 milli-meters, the internal area is 0.0177 meters squared – this is calculated using the equation $S = \pi \frac{d^2}{4}$. Finally, the time constant is calculated using the equation $\tau = SR$. This gives the calculated time constant as 84.823 when applied to experimental values.

Both time constants as well as the percentage difference between the two is detailed below in table 1 with the change in water height over experimental period being shown in graph 1.

Calculated τ	84.823	s
Estimated τ	64.148	s
Δτ	20.675	s
Percentage Difference	24.374	%

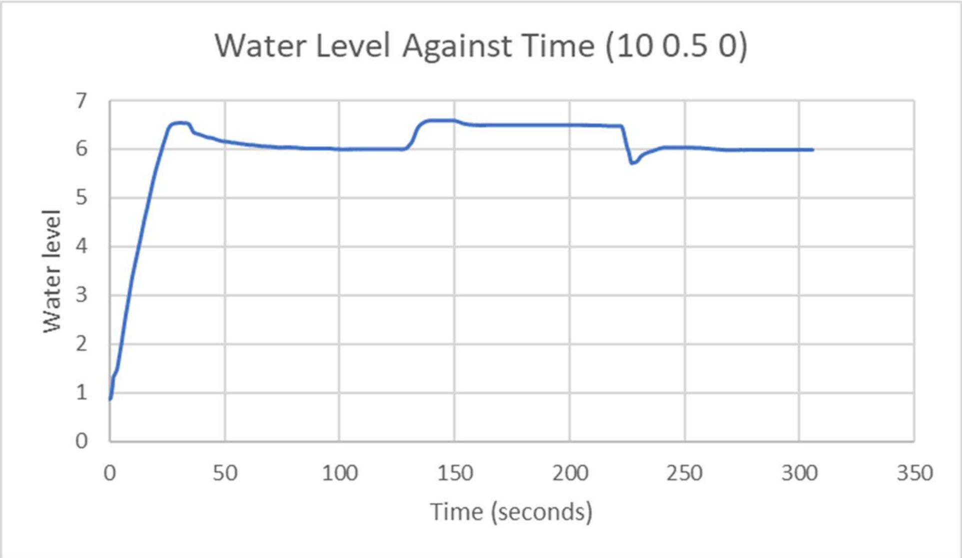
Table 1 – Time Constants



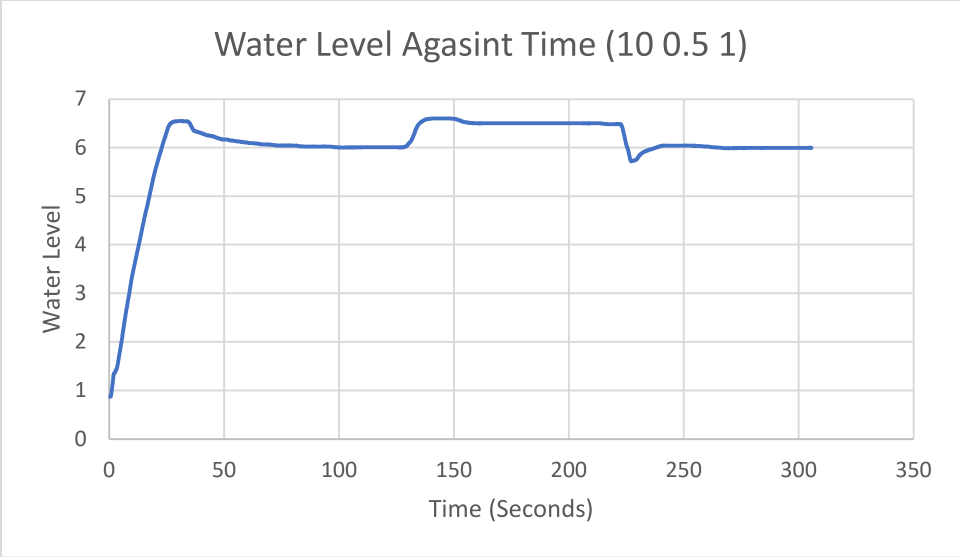
Graph 1 – Water level over test period

<u>4.2 Closed-loop</u>

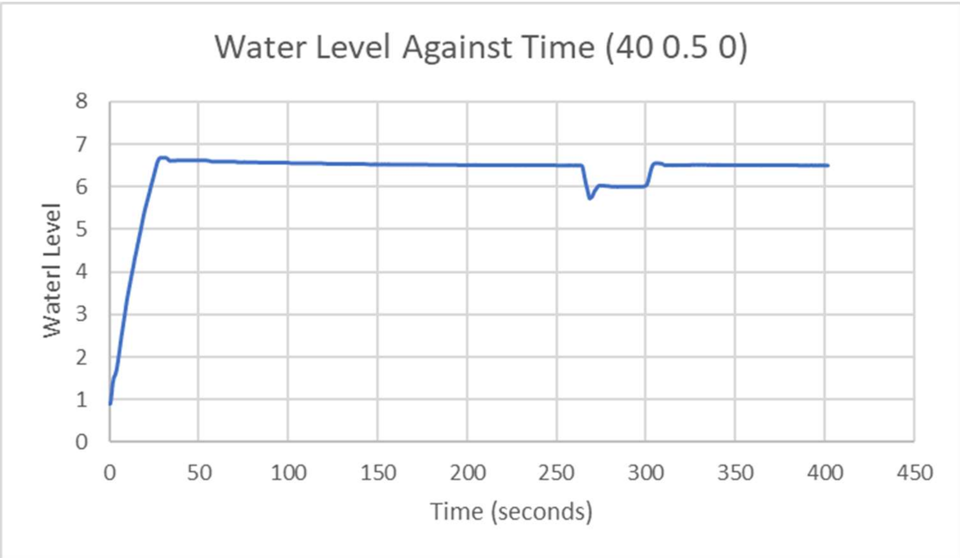
The results of the closed loop procedure centred around graphing the water level over the test period for each version of the PID controller. There was no calculation required. The graphs associated are displayed below.



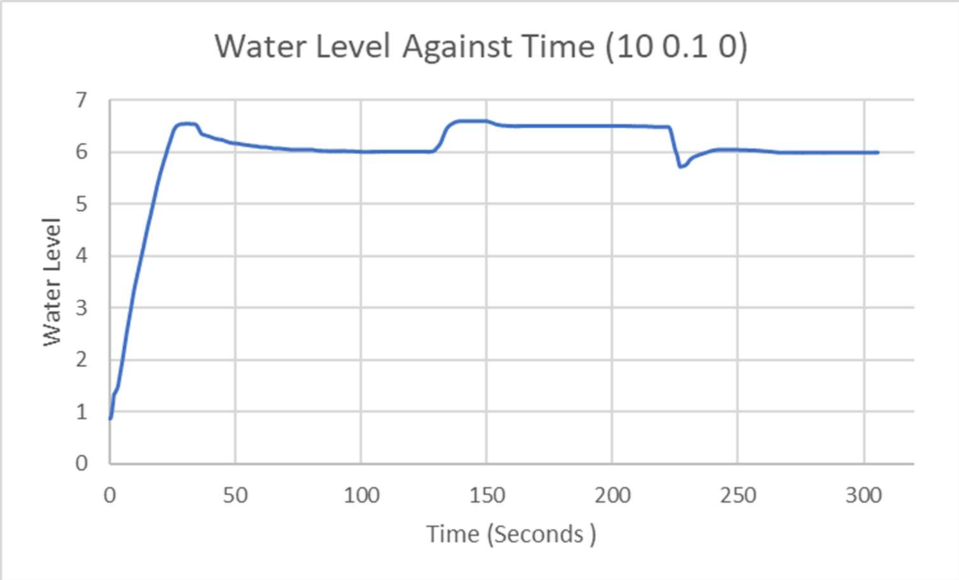
Graph 2 – Water level over experimental period (PID constants 10, 0.5, 0)



Graph 3 – Water level over experimental period (PID constants 10, 0.5, 1)



Graph 4 – Water level over experimental period (PID constants 40, 0.5, 0)



Graph 5 – Water level over experimental period (PID constants 10, 0.1, 0)

5. Discussion

By ay of completing the laboratory, all stated aims were achieved and both procedures were completed. Across the two tests, two sets of results were found: the time constants for just the open-loop procedure as well as graphs displaying the water level across the experimental period which applied to both open and closed loop procedures.

5.1 Open-loop

The relationship between the estimated and calculated time constant is an indicator of the experimental accuracy in the lab. It is clearly shown in the percentage difference – of around 24% - that there is significant disparity between the values. This shows that the open loop system is largely inaccurate which is to be expected given the lack of feedback integrated into the system.

Graph 1, which details the water level across the experimental time, displays pertinent information regarding settling time, rise time, amplitude, and overall response of the system. The time taken to reach water level A is around 550 seconds. This demonstrates a significant rise time for the system to reach rest. To reach level B, the time taken is around 101 seconds. Much like for level A, the graph indicates a significant settling time. Since the system is open, the extreme rise time is to be expected. This is because, unlike closed feedback systems, open-loops will not overshoot and aim to correct – instead slowly rising based on a set input (voltage in this case).

The usefulness of the open loop system is massively limited due to its lack of feedback loop and thus any method of optimisation. This limits its used to simple systems which do not require a rapid response since the system cannot correct itself based on sensors – such as in the case of a time-based thermostat.

5.2 Closed-loop

The graphs associated with the closed loop procedure detail the water level across the test period for each variant of the PID controller.

The initial PID values resulted in a response with significant amplitude and settling time, as show in graph 2. When increasing the differentiation constant to 1, with all other constants remaining the same, there is no clear change in response time or amplitude – as seen in graph 3. Graph 4 displays the PID controller when the proportionality constant is increased to 40 and all other constants remain at initial values. In this case, the amplitude is drastically improved (minimised) however the settling time is extended. The graph (graph 5) displays the system reaction when the Integral constant is minimised. This results in an almost identical response to the initial PID controller.

In general, these systems had a fast rise and settling time but had large amplitude overshoots. These system characteristics are to be expected because of a closed loop system. The accelerated rise time leads to a large overshoot which is then corrected by the feedback response of the system. This means that the system can take advantage of a quick rise while having the ability to compensate the drawbacks.

5.3 Evaluation

When comparing open and closed loop systems, closed systems which integrate feedback loops are far more responsive. This is displayed, in graph 4, through the reduced settling time, by around half, alongside the minimal rise time associated when compared to the open loop, displayed in graph 1. However, when analysing amplitude, the open loop response is less severe than the unoptimized closed loop systems. This is an inherent issue with closed loop systems which can become catastrophic if not addressed; the main way to optimise a system in our case is through a PID controller.

The disparity between the different PID controls demonstrates the importance of optimisation within closed loop systems. As displayed in graphs two through five, the constant of most importance was the proportionality constant – having the largest positive impact of system response (improving rise, settling and overshoot characteristics) when increased. If the PID values are unoptimized, this can be catastrophic for the system, leading to huge overshoots and extended settling times. Due to this, it can be determined that the PID controllers are exceedingly crucial to the successful optimisation of a system for any given task – even becoming functionally useless if the PID controller is sufficiently unoptimized.

One issue to note, is that the accuracy of the data accumulated in the laboratory may have been affected by experimental error. While the lab technician was present to negate most user error, parallax was still present during the interpretation of the ruler on the external of the process vessel. This could have induced error in the initial water level readings leading to the significant percentage difference between the estimated and calculated time constants. Use of the level transmitter during this stage could have negated this issue.

6. Conclusion

Overall, through the completion of both water level control procedures, all stated lab objectives were completed and a greater level of practical understanding of PID controllers, open and closed loop systems was gained. In reference to procedure one, the estimated time constant was found as 64.148 whereas the calculated constant was found as 84.823 – resulting in a percentage disparity of 24.374%. All experimental data was graphed for both procedures – as shown within the results section of this report – with the graphs associated with procedure two mostly matching the simulated responses in *MATLAB*. In general, it can be determined that optimised closed loop systems which integrate feedback loops are far more responsive. The PID controller itself is exceedingly useful for the optimisation of systems, controlling characteristics of the systems response. This means each system can be optimised for a particular use case, with poor optimisation having a detrimental response.

7. References

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