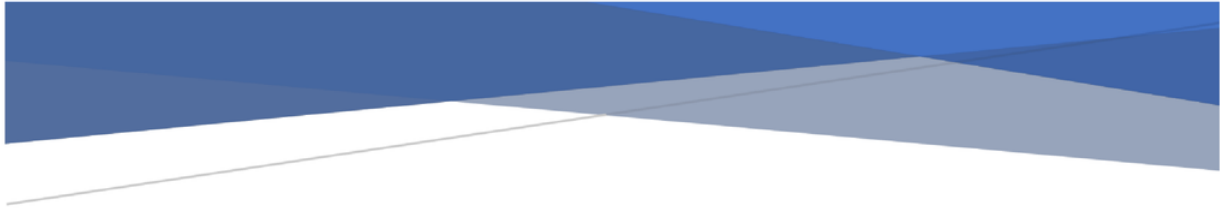


M7X01643 James Neucker

by James Marshall Neucker

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INSTRUMENTATION AND CONTROL

M7X01643

Abstract

This assignment contains the selection of components for a pH control system and the analysis of the results of the simulation that has been constructed

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Introduction

The aim of this assignment is to design a CO₂ dosing system that regulates the acidity of water leaving a treatment plant. The dosing system is to be fitted near the exit of the treatment process. The water that is to be treated is currently between Ph 8.5-13, the Ph of water that leaves the plant should be in the range of Ph 6.5-7.5 if the water exceeds this range there is potential for the site to be fined. The dosing system consists of a CO₂ tank, proportional gas valve, diffuser and Ph sensor.

Process Control Systems

A control system is used to control a measurable variable to ensure the system is required to operate at a set value, i.e. temperature, or to ensure a sequence of events occur depending on measured conditions or system inputs.

Feedback is required to allow a control system to control events that allow appropriate responses to changing measurables. Feedback control signals are fed from the output to a comparator to allow appropriate events to occur to control the variable that is being measured. Most systems that have a comparator are closed loop systems that used negative feedback to adjust the processes that occur.

The comparison element is used to compare the achieved output value for the variable to the reference value where,

$$\text{error signal} = \text{reference value} - \text{measured value}$$

Equation 1: Comparison calculation

A control element is where the error signal is received and computed to ensure the system performs a function such as opening a valve. These can be fixed and are termed hard wired systems, or they can be programmable systems that allow control plans to be stored in a memory system that can be rewritten.

The correction element changes the performance of the process and as a result the condition that is being controlled.

The process element is the environment and condition that is being controlled by the system.

The measurement element is the device that is used to monitor the condition that is required to be controlled such as the pH sensor used in this assignment.

Proportional plus derivative (PD) control

Derivative control is rarely used by itself as the system when subjected to an error signal that is steady does not allow the system to produce an output and as a result there will not be any correction of the signal by the system, for this reason it is combined with proportional control.

$$\text{controller output} = K_p e + K_D \frac{de}{dt} [1]$$

Equation 2 : Proportional plus derivative control output

Where;

K_p = Proportionality constant

K_D = Derivative constant

$\frac{de}{dt}$ = Rate of change in error

PD system transfer function is given by,

$$\text{controller output } (s) = K_p E(s) + K_D s E(s)$$

Equation 3 : PD system transfer function

With the transfer function $K_p + K_D s$ is

$$tf = K_D \left(s + \frac{1}{T_D} \right) [1]$$

Where $T_D = K_D / K_p$ is the derivative time constant.

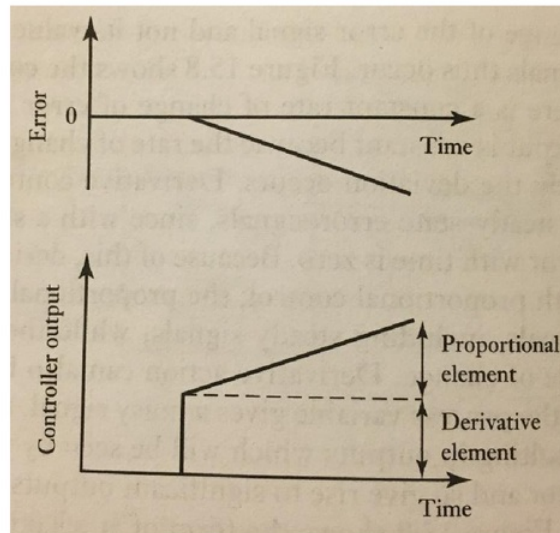


Figure 1 : PD Control [1]

Figure 1 shows the output of the controller changing with a error signal that is continually changing. Initially the system responds quickly by altering the output as the derivative action combined with the slower change from the proportional action of the system, this does lend the system to fast changes in the process that is controlled.

Integral Control

Integral control is a mode of control that allows the rate of change for the control output to be proportional to the signal that is input as an error signal.

$$\frac{dl}{dt} = K_I e$$

Equation 4: Integral mode of control

Where;

$$K_I = \text{Constant of proportionality}$$

The units for above are 1/s and if integrated gives the following;

$$\int_{I_0}^{I_{out}} dl = \int_0^t K_I e dt$$
$$(I_{out} - I_0) = \int_0^t K_I e dt$$

Where:

$$I_0 = \text{controller output at time zero seconds}$$

$$I_{out} = \text{output at time } t$$

By taking the Laplace transform

$$(I_{out} - I_0)(s) = \frac{1}{s} K_I E(s)$$

Giving the transfer function as

$$t.f = \frac{1}{s} K_I$$

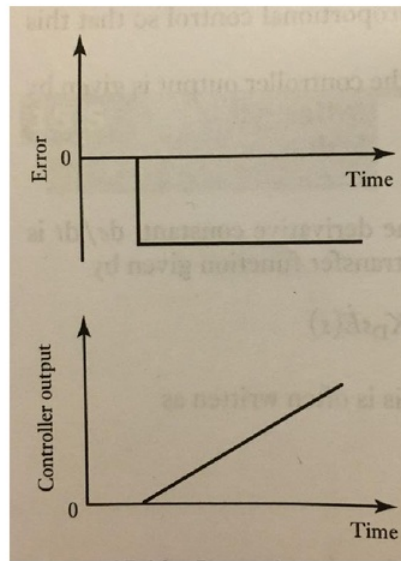


Figure 2 : Integral Control [1]

Shown by figure two is the reaction of the integral controller when the system receives a constant error to the controller. When there is a constant controller output there is zero error, as the controller output changes with a constant rate the error is of a uniform value.

The graph can also be understood in terms of the area under the error signal;

$$\text{Area under graph from } t = 0, t = \int_0^t e \, dt$$

Until there is an error greater than zero the integral value is also zero with $I_{out} = I_0$. As the error is emitted it is of a constant value, resulting in the area under the graph increasing with time. With the area increasing at a constant rate the controllers output will increase at a constant rate.

Proportional plus integral (PI) control

The integral mode of control is commonly paired with the proportional mode of control system to provide a controller output shown below.

$$\text{controller output} = K_p e + K_i \int e \, dt$$

Where:

K_p = proportional control constant

K_i = integral control constant

e = error e

The transfer function for the (PI) control is;

$$tf = K_p + \frac{K_I}{s} = \frac{K_p}{s} \left(s + \frac{1}{T_I} \right)$$

Equation 5: PI control transfer function

Where;

$$\text{integral time constant} = T_I = K_p / K_I$$

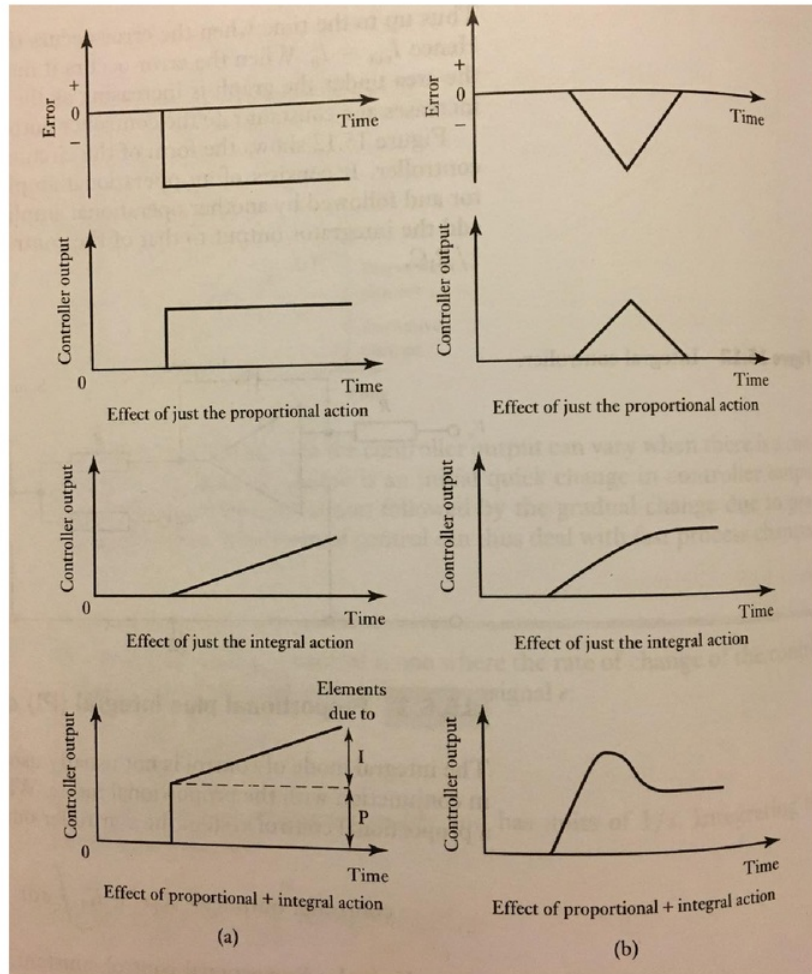


Figure 3 : PI Control [1]

Figure three (a) represents how the system performs when subjected to a rapid change in a constant error, the error produces a proportional controller output that is constant because of the error remaining stable, the controller output is then increasing at a steady rate due to the product of the integral.

Figure three (b) shows how the integral and proportional action is affected by an error signal that increases from zero to a value then back down to zero, from the proportional action the change is replicated and returns to the original value, with the integral action the controller output is seen to increase proportionally to the increase in the area under the graph for error-time. There is still a value for area under the graph when the error is brought back to zero, the controller output changes continue after the error signal has stopped.

PID controller

When the three types of control discussed are combined, proportional, integral and derivative control the result is a system that is commonly referred to as a three-mode controller or PID controller.

$$\text{controller output} = K_p e + K_I \int e \, dt + K_D \frac{de}{dt}$$

Where;

$$K_p = \text{proportionality constant}$$

$$K_I = \text{integral constant}$$

$$K_D = \text{derivative constant}$$

When taken in the Laplace form the controller output is given as;

$$\text{controller output } (s) = K_p E(s) + \frac{1}{s} K_I E(s) + s K_D(s)$$

And the transfer function is given as;

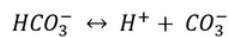
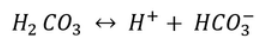
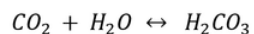
$$tf = K_p e + \frac{1}{s} K_I + s K_D = K_p \left(1 + \frac{1}{T_I s} + T_D s \right)$$

Equation 6: PID transfer function

Critical Instrumentation Evaluation

The system that is required to be controlled as part of this assignment is a CO₂ dosing system that will regulate the pH of the waste water that is leaving a waste water treatment plant, the dosing system is to be fitted in a location upstream to the exit of the water from the plant. The target pH for the waste water is pH 6.5-7.5.

The CO₂ that is released into the waste water by the system is required to reduce pH of the water, to do this the pH that is released goes through the following chemical reactions;



CO₂ when dissolved forms carbonic acid which dissociates into bicarbonates, carbonates and Hydrogen ions as a result of the increase in Hydrogen ions the pH of the water reduces, a pH sensor utilises the amount of Hydrogen ions that are positively charged to with an acidic solution having a higher amount of positively charged ions present with an alkaline solution having less, the pH sensor measures the electrical potential that is produced by the solution it is immersed in and then compares it to a constant value that is predetermined.

A pH sensor that is digital will produce an electrical signal that is proportional to the pH of the solution, this is completed by passing electricity through the solution this is then measured to quantify the electrical potential of the solution.

System Block Diagram

The block diagram for the system is shown below;

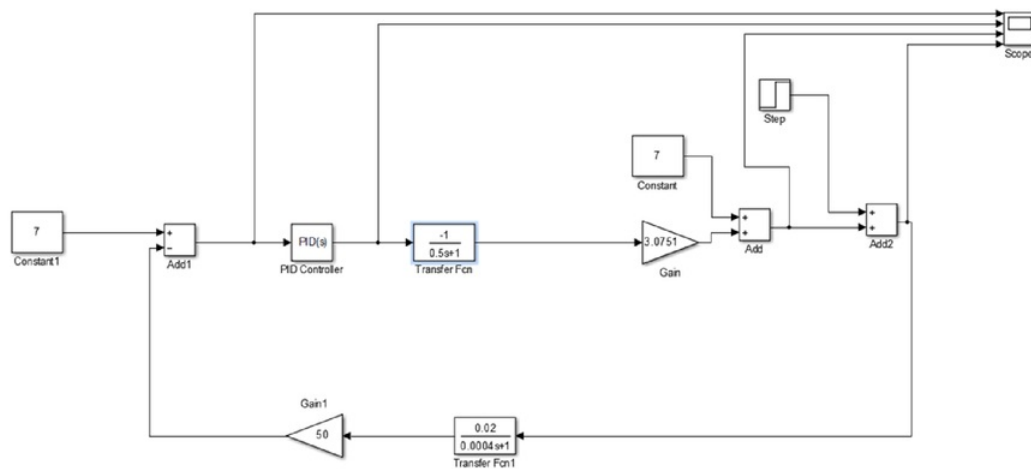


Figure 4 : System block diagram

Transfer Functions for the System

The pH sensor that is used for the dosing system is the Yokogawa pH sensor;



Figure 5 : Yokogawa pH sensor [2]

'The electromotive force (emf) of a pH sensor varies with temperature. This is because the potential generated at the glass membrane is proportional to absolute temperature, T, as indicated by the Nernst equation. Electromotive force, E, is expressed by equation' [2]

$$E = T \cdot m \cdot (7 - x) + EAS$$

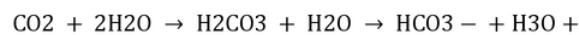
(Where: T: absolute temperature m: constant (≈ 0.198) x: pH value EAS: asymmetry potential [2])

To determine the transfer function for the block that was inserted into the system model the parameters were determined to be;

$$\text{block t.f parameters} = 0.5 s + 1$$

Relative flow of the water across the sensor and CO₂ as the measure of the chemical reaction of the CO₂ in the water is inversely proportional to the temperature of the solution.

The gain of 3.0751 is the maximum pH change to scale the t.f. to the pH scale. The gain was calculated by utilising the value for the pKa of carbonic acid which is 6.367, the solubility of CO₂ in water at 25 degrees Celsius and atmospheric pressure is 1.45g/l in the following calculations;



The carbon dioxide that dissolves into water in moles at equilibrium will be the same as the carbonic acid moles in the solution.

$$1.45\text{g CO}_2 \frac{1\text{mol}}{44.01\text{g}} = 0.032947 \text{ mol CO}_2$$

This was then converted from pKa to Ka;

$$10^{-pKa} = Ka \rightarrow 10^{-6.367} = Ka$$

$$Ka(10^{-6.367}) = \frac{[A^-][H^+]}{[HA]} = \frac{(x)(x)}{(0.0329 - x)}$$

The rule of 500 could be applied as the criteria was met, if $[H^+] Ka > 500$, ignore any nonzero changes in "x"

$$\frac{0.0329}{10^{-6.367}} = 76594 \gg 500$$

Therefore, the rule of 500 can be applied.

Simplified Ka;

$$10^{-6.367} = \frac{x^2}{0.0329}$$

$$x^2 = 10^{-6.367}(0.0329) = 1.41317 \times 10^{-8}$$

$$x = \sqrt{1.41317 \times 10^{-8}} = 1.18877 \times 10^{-4} = [H^+]$$

$$pH = -\log[H^+] = -\log(1.18877 \times 10^{-4}) = 3.9249$$

The pH can drop to 3.9249 in 1 litre of H₂O in equilibrium with 100% CO₂ @ 25°C and 1 atmosphere of pressure, as the reference (constant) is set to seven this allows the system to operate at pH other than 7 or neutral.

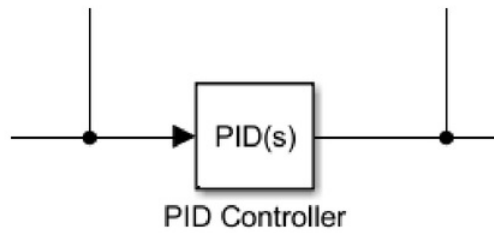


Figure 6 : Systems PID Controller

C =

$$K_p + K_i * \frac{1}{s} + K_d * \frac{s}{T_f * s + 1}$$

with $K_p = -0.138$, $K_i = -0.48$, $K_d = 0.0549$, $T_f = 0.399$

Figure 7 : Transfer Function for PID Controller

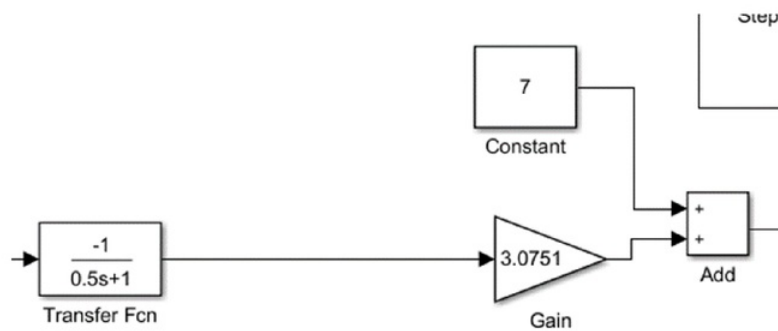


Figure 8: Block Diagram for plant from Simulink

Where the relative flow of water and CO₂ and is measure of the chemical reaction in water that is inversely proportional to water and is represented by the following transfer function;

$$\frac{-1}{0.5s + 1}$$

The Gain is set to 3.0751 to ensure the transfer function is amplified to the pH scale set at 7. With the overall plant transfer function shown below;

$$\frac{-1.538e04}{s^2 + 2502 s + 5000}$$

Figure 9: Overall Transfer Function for the Plant

The transfer function for the sensor is shown below;



Figure 10: Block Diagram for the Sensor from Simulink

```

sensor =

      0.02
-----
0.0004 s + 1
  
```

Figure 11: Transfer function of sensor

For the whole block diagram of the system, a transfer function was produced through MATLAB and is shown below;

```

system =

From input "ufb" to output "ufb":
      5.079 s^6 + 2.542e04 s^5 + 3.189e07 s^4 + 1.897e08 s^3 + 3.681e08 s^2 + 2.322e08 s
-----
0.0004 s^9 + 3.004 s^8 + 7527 s^7 + 6.318e06 s^6 + 5.659e07 s^5 + 1.908e08 s^4 + 2.868e08 s^3 + 1.647e08 s^2 + 4.645e06 s
  
```

Figure 12: Transfer Function for whole system

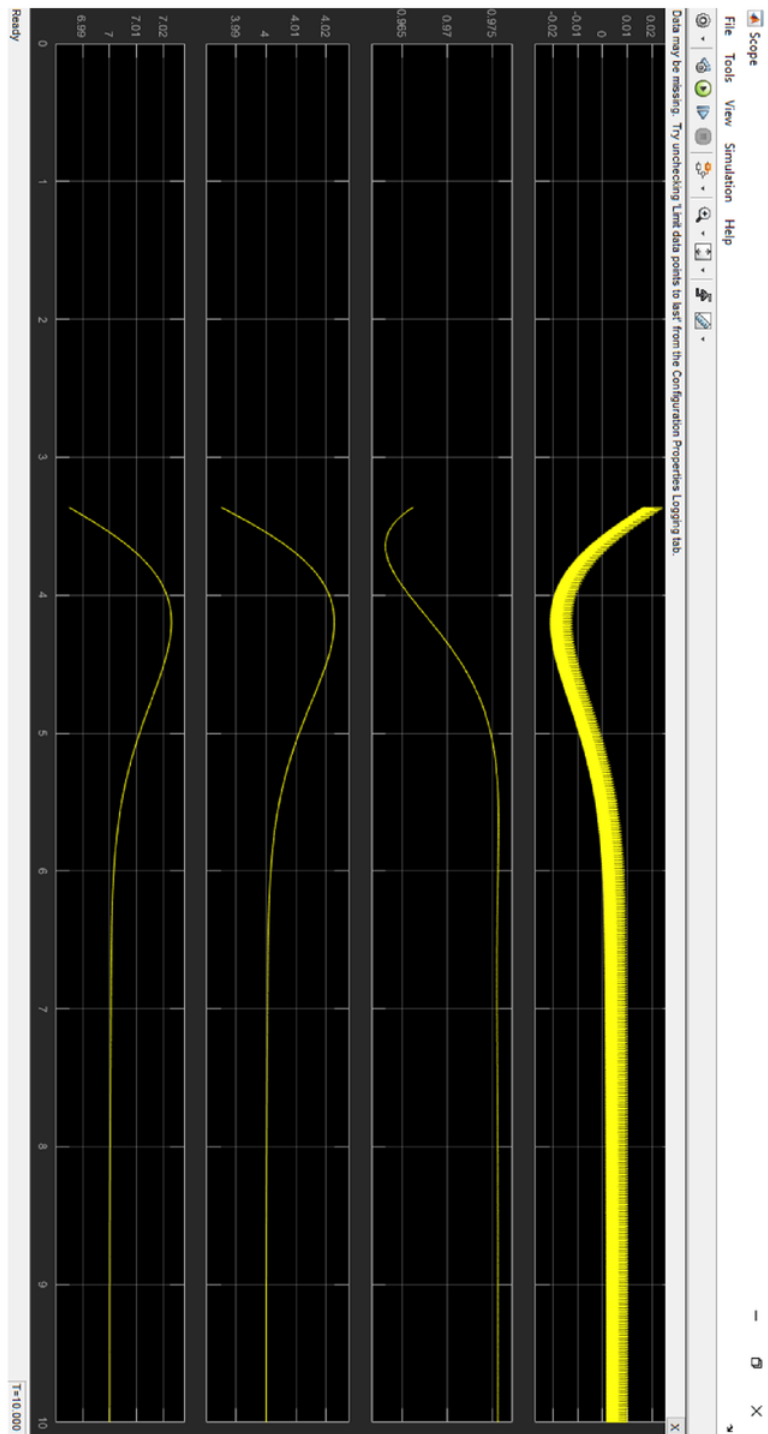


Figure 13: System Scope Graph Results

Bode Plot for System Stability

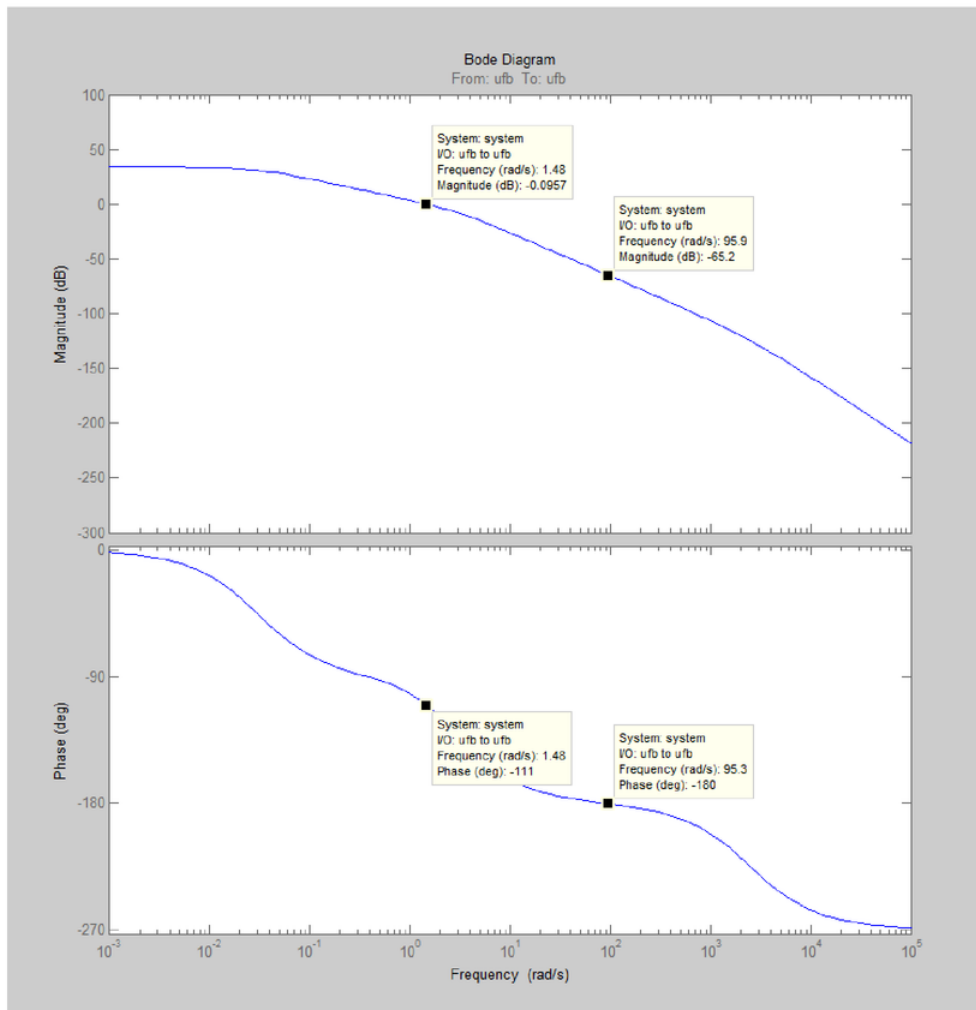


Figure 14: System Bode Plot

The Bode plot above represents the frequency response of the system for values the Magnitude and the Phase angle, both are required to be analysed for a system as they are representative of the input signal that is sinusoidal in nature. The top graph shows the decay of the magnitude of the system and the bottom represents that phase angle when the sinusoidal input is varied across a frequency range. Both graphs are plotted with a x axis that is logarithmic.

Pole Zero Plot for System

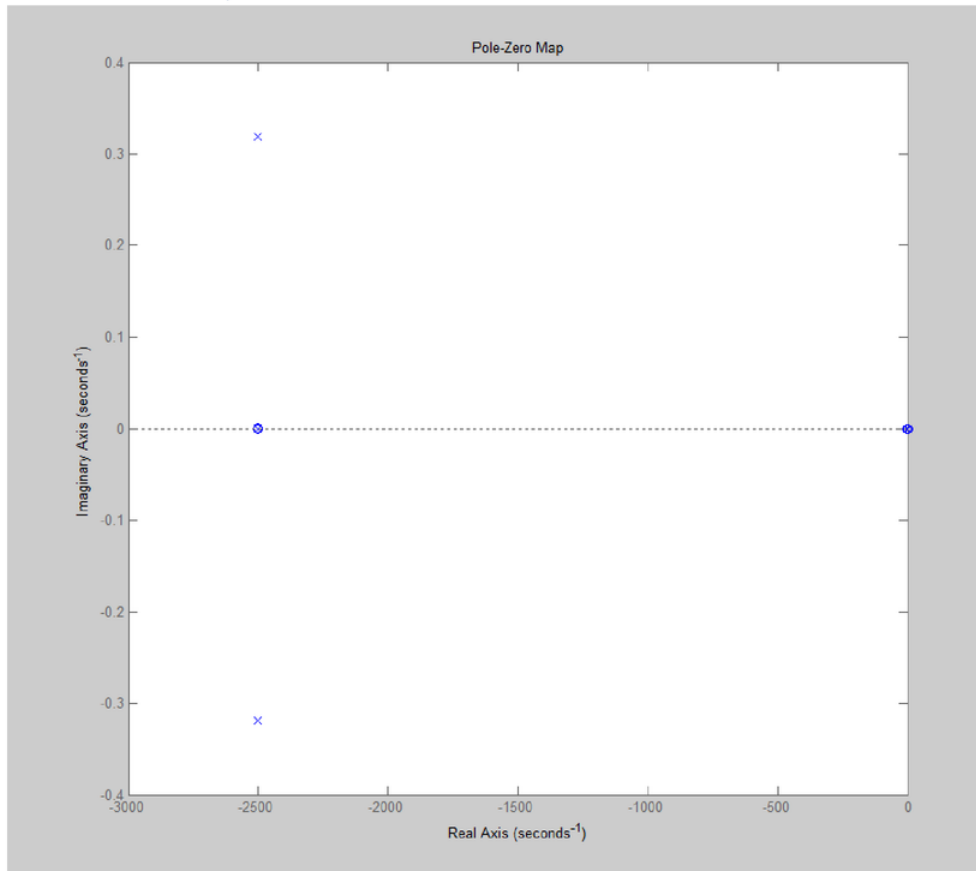


Figure 15: Pole Zero Plot for System

As the system utilises negative feedback the input and feedback signals are subtracted when passed through the summing block shown on the left of the block diagram, to determine if the system is stable the pole zeros must be plotted to evaluate their position and whether they are located on the left of the real axis. The Bode plot in figure 15 shows that for this system, and the systems transient response will decay in time allowing the system to achieve steady state.

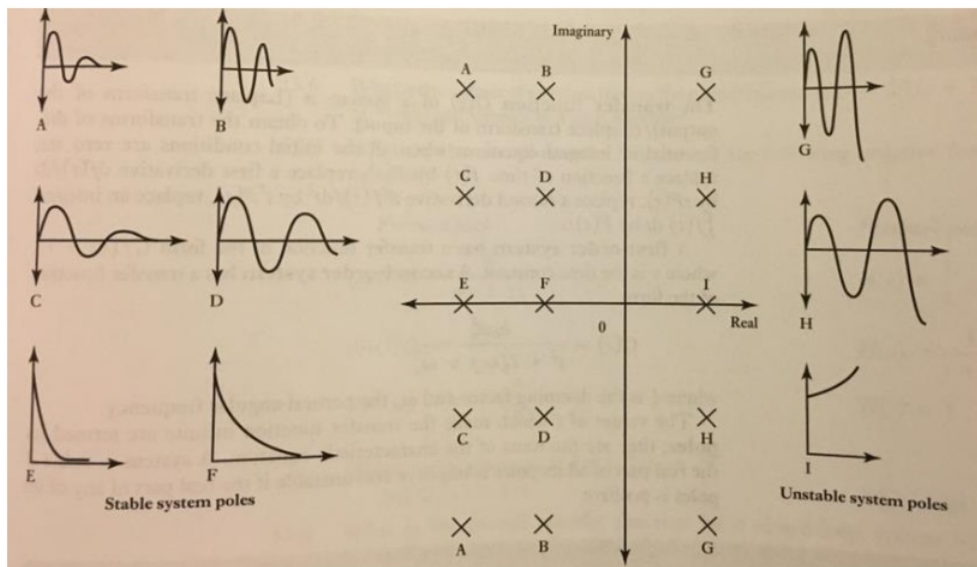


Figure 16: Pole Zero Stable and Unstable Plots

[1]

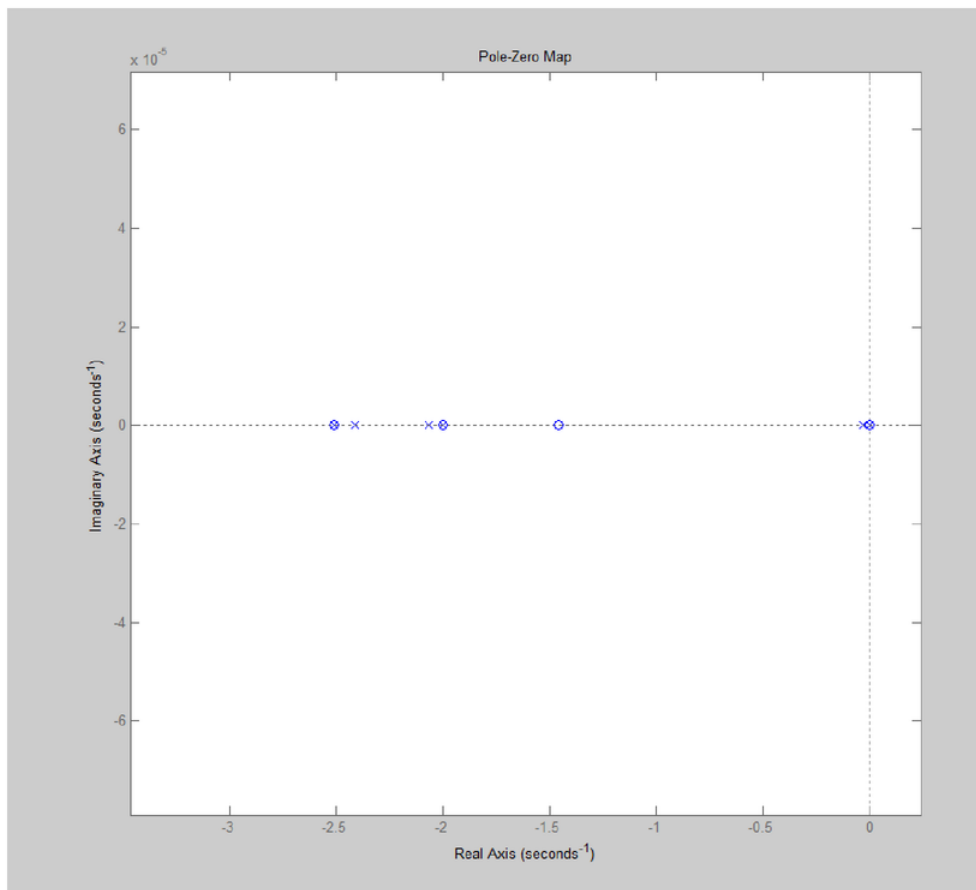


Figure 17: Pole Zero Plot Zoom

Figure 16 shows that the system has reached steady state and the transient response will not increase resulting in an unstable system.

Nyquist Plot

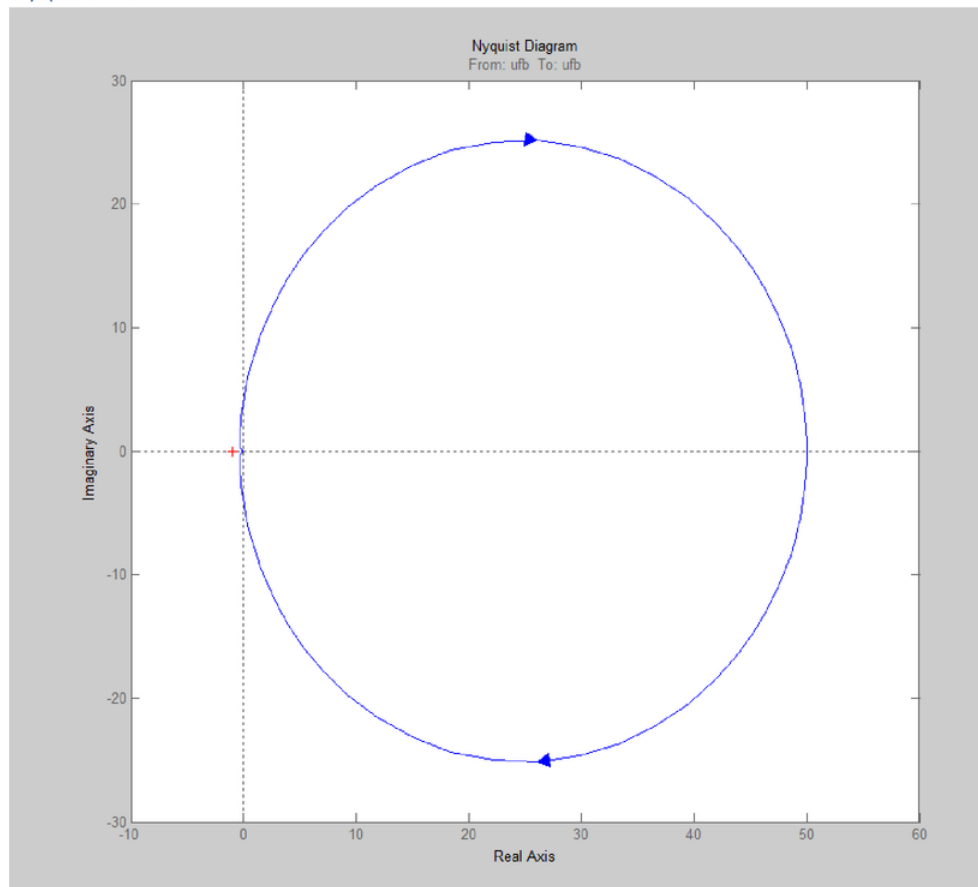


Figure 18: Nyquist Plot for the System

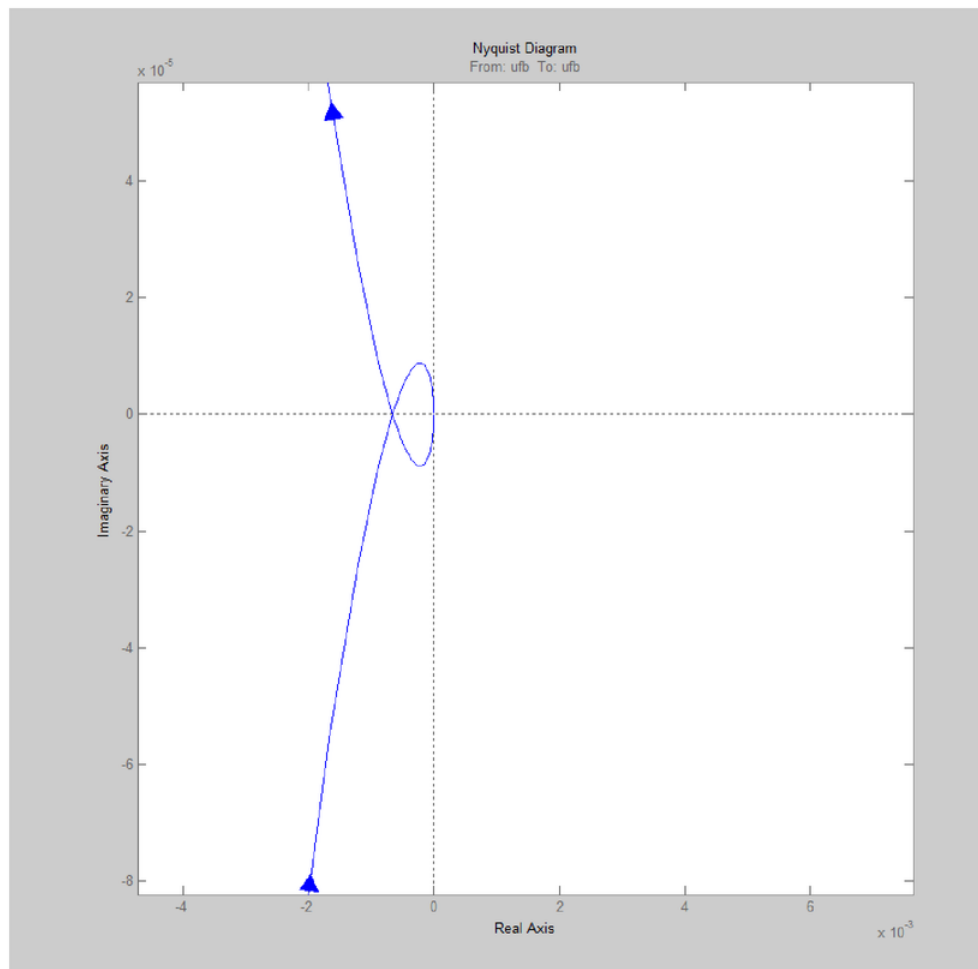


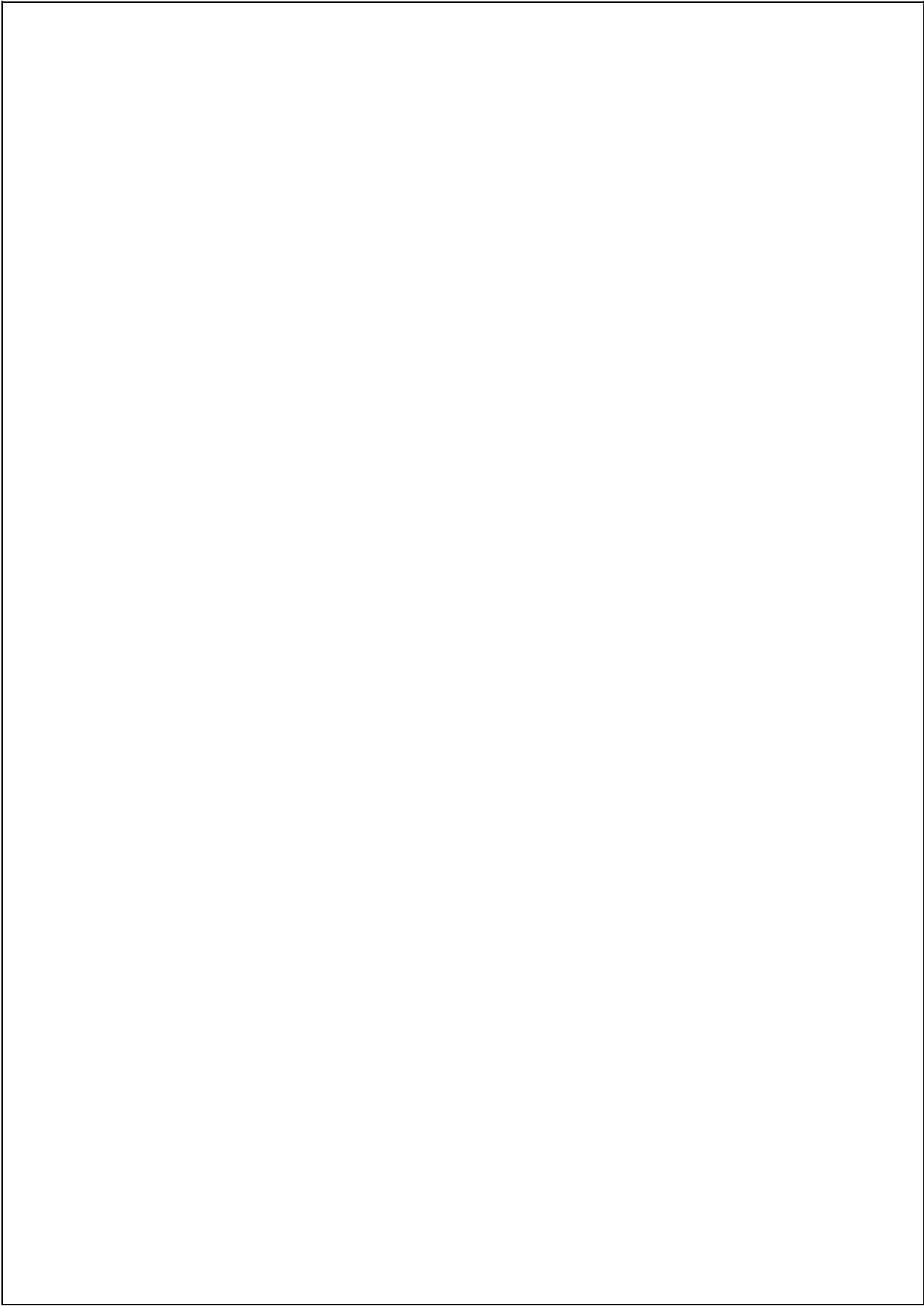
Figure 19: Nyquist Plot Zoom

Conclusion

In conclusion the system that was designed in Simulink with the aid of the pH sensors design specification allowed a model to be constructed and tested to prove that a system can be constructed that will maintain steady state behaviour when subjected to rapid changes in pH.

References

- [1] W.Bolton, Mechatronics, London: Pearson Education Ltd, 2011.
- [2] yokogawa, "<https://www.yokogawa.com/solutions/products-platforms/process-analyzers/liquid-analyzers/ph-sensors/differential-phorp-sensors/#Downloads>," yokogawa, 2017. [Online]. Available: yokogawa. [Accessed 2018].



FINAL GRADE

GENERAL COMMENTS

Instructor

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Comment 1

Why have you chosen these values?



Comment 2

I think you mean...

"The amount of carbon dioxide in moles that dissolves into water at equilibrium..."

The order of the words in your sentence make it sound like the water is contained in small furry subterranean animals, but I'm sure that is not what you meant. :)

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GRADING FORM: SMU GENERIC_GJ

JAMES MARSHALL NEUCKER

63.45

RESEARCH-INFORMED LITERATURE



You have referenced a very limited number of sources. Your background section is very brief, I would have liked to see more information about pH sensing and how this relates to your task.

7.95

KNOWLEDGE AND UNDERSTANDING



Accurate knowledge and good understanding of the topic, although several key bits of information are missing from the construction of your system; such

15.25

as why you chose the values in the denominator of the plant transfer function.

ANALYSIS



You have performed an analysis of your control system, but you have not discussed the results to any length.

15.5

PRACTICAL APPLICATION AND DEP.



A very good application of the available tools.

18.75

SKILLS FOR PROFESSIONAL PRAC.



Can communicate effectively although your report seemed slightly disjointed in places and could have flowed better.

6