Control Systems in Vertical Growing Systems

Nutrient and pH control of vertical growing systems

Master's thesis in Communication Engineering

ANDREAS ANDERSSON, OSCAR WALLIN

DEPARTMENT OF ELECTRICAL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
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Andreas Andersson, Oscar Wallin

Supervisor: Name, Richard Kahl, Sigma Embedded Engineering
Examiner: Torsten Wik, Automatic control research group, Chalmers University of Technology

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Department of Electrical Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Visualization of a growing cart used for testing.

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Abstract

Growing plants with hydroponics can reduce the use of water to 10% of that of traditional farming. Hydroponics puts high demands on the pH and nutrient levels of the water. Therefore, a major challenge is the control of pH and nutrients, often measured as electrical conductivity (EC).

This master thesis goes through experiments that has resulted in a model of EC and pH, for a hydroponic farm, as well as a fuzzy-logic control system and PID control system for pH and EC.

The PID controller outperforms the fuzzy logic controller when used for pH control, in both speed and stability. For EC the PID controller was faster but less exact when compared to fuzzy logic control. Both a fuzzy control system and a PID control system could be suitable for hydroponics depending on the tuning. The tuning along with the capabilities of the pumps is the determining factor for how large or small the system can be. For a small system of 20 liters the system developed in this report works well and could also be used for larger systems, but with a slower response.

Keywords: Vertical farming, Hydroponics, pH, EC, Nutrients, Control system, fuzzy-logic, PID.

Acknowledgements

We would like to thank Cecilia Vidlund and Richard Kahl at Sigma Embedded Engineering for guiding us. Green City Farmings Christer Tilk for helping us build the growing system. Our examiner Torsten Wik. Lastly we would like to thank Teknologtryck for the company and coffee.

Andreas Andersson and Oscar Wallin, June 12, 2023

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1

Introduction

This section describes the background and purpose of this thesis work. First, the problem is presented and why a solution for it is important. Then, the purpose is stated describing what the work has strived to achieve.

1.1 Background

Hydroponics is a method to grow plants and crops using nutrient solutions in water instead of traditional soil [1]. This has proved to need only about 10% of the water that a traditional farm would need for the same amount of produce [2].

Figure 1.1: An example of a simular hydroponic system

The nutrient composition and pH levels are very important in hydroponic farming to utilize the advantages of the enhanced environment. In hydroponic farming the pH and electrical conductivity (EC) are values that need to be monitored to supervise the nutrient status [3]. Controlling these values is key to secure a good product of a hydroponic farm. The reason why the pH-level is so important is because it affects the plants' ability to absorb certain micronutrients. The EC-value can be used as an indicator of macro nutrients in the water and since most of the salts in fertilizer are macro nutrients the EC becomes very important. Regular monitoring of the pH and EC can prevent almost all nutrient-related problems for the crops since it becomes possible to detect problems before they affect the crops' health and growth. This will increase the amount of healthy crops and reduce waste [4]. Other important aspects of the growing environment are humidity, water temperature, and room temperature, these also need to be monitored and controlled. There are solutions to automatically track and regulate these values, but current automation solutions are expensive and therefore not feasible for smaller installations [5]. This thesis work has been written with the help and collaboration of Green City Farming.

1.2 Purpose

This master thesis work strives to design and make an alternative for automatically controlling water quality and monitoring the growing environment for small-scale vertical growing systems. The thesis will also include a comparison between a PID and a fuzzy logic system to determine that which performs better for the modular system.

The following are the research questions this thesis are aiming to answer.

- What sensors are best at measuring and monitoring EC, pH, temperature and humidity in a hydroponic system over a longer time period?
- Is there a way to simulate pH and nutrient content to create control systems easier?
- What systems can be used for controlling and stabilizing the pH and nutrient levels and what system performs the best?
- Which is the best way to implement sensors, software and control systems to keep track of and control the water quality?

2

Theory

2.1 pH

pH is the negative logarithm of hydrogen-ions in the solution. Controlling the pH is done by adding the concentration of either a base- or acidic solution to the water. Acids increase the amount of hydrogen ions in the solution while bases decrease the amount of hydrogen ions in the solution [6]. There are many different acids and bases all with different pH signatures and equivalence points. An equivalence point is the point where the change in pH is the most rapid and the point where the amount of acid and base neutralize each other

$$V_b \cdot M_b = V_a \cdot M_a, \tag{2.1}$$

where V_b is the volume of the added base, M_b is the molarity of the base, V_a is the volume of the addded acid and M_a is the molarity of the acid. A slight addition of acid or base can change the pH of the solution by multiple units around this point. A common choice is to use phosphoric acid to decrease the pH because it does not change rapidly in the typical control range of pH 5.5-6.5 [7][8]. This is a polyprotic acid, which means that it has multiple equivalence points. The reason for this behavior is that the available ionizing hydrogens do not dissociate from the acid at the same time [8]. The relation between equalization points is described by the disassociation constants. To calculate these for an arbitrary acid one would set up a reaction equation like

$$[HA] \leftrightharpoons [H^+] + [A^-] \tag{2.2}$$

where $[H^+]$ and $[A^-]$represent the concentration of positively and negatively charged ions and $[HA]$ represents the concentration of an acid in water. From this, the disassociation constant can be calculated as

$$K_a = \frac{[H^+][A^-]}{[HA]}. \tag{2.3}$$

In the case of acids, the dissociation constant is designated as K_a and determines when the protons in the acids disassociate. In the case of polyprotic acids the initial acid will look like $[H_iA]$ where i represents the amount of hydrogen ions and A represents the remaining compounds of the acid. The steps taken in
Equation (2.2) and (2.3) can be repeated until no hydrogen ions are left to disassociate to calculate all the disassociation constants $K_{[ai]}$ [9]. Explicitly we can write the disassociation reactions for a triprotic acid as

$$
\begin{aligned}
H_3A &= H^+ + H_2A^- \qquad && k_1 = K_1 \\
H_3A &= 2H^+ + H_A^2 \qquad && k_2 = K_1K_2 \\
H_3A &= 3H^+ + A^{-3} \qquad && k_3 = K_1K_2K_3
\end{aligned}
\tag{2.4}
$$

to show the cumulative release of H^+ ions, while the option shown in Equation (2.3) shows the step-by-step release.
The water contributes to the pH concentration, and the self-ionization of water is defined as

$$H_2O = H^+ + OH^- \tag{2.5}$$

with a dissociation constant of

$$K_w = [H^+][OH^-], \tag{2.6}$$

where $K_w = 1.02 \cdot 10^-14$ in $25°C$[10]. By rewriting Equation (2.6) as

$$[OH^-] = \frac{K_w}{[H^+]} \tag{2.7}$$

and introducing $w([H^+])$, defined as

$$w([H^+]) = [OH^-] - [H^+] = \frac{K_w}{[H^+]} - [H^+], \tag{2.8}$$

Which will allow for removal of the H_2O component of the acid-base-water system.

The acid dissolves into different acid species based on the amount of hydrogen ions in the original acid. To describe this behavior, ionization fractions can be used,

$$a_j = \frac{[j]}{C_T} \tag{2.9}$$

where $[j]$ represents the the molar concentration of the jth disassociation step, and C_t represents the total acid concentration, which can be represented as

$$C_T = \sum_{j=0}^{N} [j] = [0] \sum_{j=0}^{N} \frac{k_j}{[H^+]^j}. \tag{2.10}$$

Equation (2.9) and (2.10) combined, result in

$$a_j = \frac{k_j}{[H^+]^j} \cdot a_0, \tag{2.11}$$

where a_j is the ionization fraction and a_0 can be described as

$$a_0 = \sum_{j=0}^{N} (\frac{k_j}{[H^+]^j})^{-1}. \tag{2.12}$$

From this it can be seen that the ionization fractions depend on the cumulative equilibrium constants and the current amount of hydrogen ions in the solution. By using what was found in Equation (2.11) and (2.12) the moment Y_L can be calculated as

$$Y_L = \sum_{j=0}^{N} j^L a_j, \tag{2.13}$$

where Y_0 represents the massbalance equation for the ionization fractions as shown below.

$$Y_0 = a_0 + a_1 + ... + a_N = 1 \tag{2.14}$$

To create a complete system from these equations, a charge balance will also be needed. The variables included will be

$$H^+, OH^-, H_N A, H_{N-1}A^-, ..., A^{-N}, B^+. \tag{2.15}$$

This results in a system with $N + 4$ variables. Here, N is the number of equivalence points for the acid in the system. The charge balance can be formulated as

$$C_B = [H_{N-1}A^-] + [H_{N-2}A^{-2}] + ... + N[A^{-N}] + OH^- - [H^+] \tag{2.16}$$

and the massbalance can be described as

$$C_T = [H_N A] + [H_{N-1}A^-] + ... + N[A^{-N}] \tag{2.17}$$

This can also be described by the ionization fractions as in Equation (2.14). The substitution of the acid species in Equation (2.16) and the division by C_T results in

$$\frac{C_B}{C_T} = Y_1 + \frac{w([H^+])}{C_T} \tag{2.18}$$

If the goal is to calculate the amount of base or acid needed to reach a certain pH, this formula will work, but the inverse task is more complicated. To do this the following

$$0 = \sum_{j=0}^{N} (x^2 + (\frac{C_B}{C_T} - j)C_t[H^+] - K_w)k_j[H^+]^{N-j} \tag{2.19}$$

will have to be used, which is a reconstruction of Equation (2.18). In the case of a triprotic acid the following equation would be the results of using Equation (2.19) [11]:

$$\begin{aligned} 0 = [H^+]^5 + [H^+]^4(k_1 + C_B) + [H^+]^3(k_2 + (C_B - C_T) \cdot k_1 - K_w \cdot k_1) \\ -[H^+]^2(K_w \cdot k_1 + (C_B - 2 \cdot C_T) \cdot k_2 + k_3) - [H^+](K_w \cdot k_2 \\ +(C_B - 3 \cdot C_T) \cdot k_3) - k_3 \cdot K_w. \end{aligned} \tag{2.20}$$

By solving for the real positive roots of $[H^+]$ a value for the amount of hydrogen ions can be calculated and thru applying the conversion from hydrogen concentration to pH gives

$$pH = -\log_{10}([H^+]). \tag{2.21}$$

2.2 EC-regulation

Electrical conductivity (EC) is a commonly used measurement in hydroponic systems. It is used to measure the ability of the water solution to carry an electrical current. The electrical current is carried by ions in the water. Any ions will contribute to the EC but salts and minerals are the main contributors to the EC. This is because when a salt dissolves, they become positively and negatively charged ions, which conduct electricity.

By measuring the EC value of water, the amount of nutrients in the water can be estimated, since the EC value is normally proportional to the amount of nutrient in the water. By measuring the EC value the need for more nutrients can be determined. If the EC levels are too low more nutrients need to be added and if it is too high more water can be added to lower it. Generally, an EC-level of around 1.2 to 2 millisiemens (mS) is recommended, but it depends on what is being grown and at what growth stare the plant is in. The EC-value does not show how much of every nutrient there is in the water but it tells you the total amount of dissolved nutrients in the water. Therefore, even if the EC value is on target there could be an uneven distribution of the different nutrients. This leads to the water having to be changed every 7-10 days for optimal conditions [12].

2.3 Control Systems

2.3.1 PID - controller

PID-controllers are widely used in different industrial control systems in a number of different areas. A PID controller calculates the error between a measured value and a desired set value. The PID then tries to reduce this error to zero. The PID uses an algorithm using mainly three different parameters, proportional (P), integral (I) and derivative (D) gain. This is done by P handling the present error, I handling the accumulation of the past errors, and D the prediction of future errors.

$$u(t) = K_P \cdot e(t) + K_I \cdot \int_0^t e(t) \cdot dt + K_D \cdot \frac{de(t)}{dt} \tag{2.22}$$

The PID controller has to be tuned i.e. the proportional gain (K_P), integral gain (K_I) and derivative gain (K_D) which needs to be determined. This tuning is important to achieve both stability and a well performing system [13]. In some cases, the PID will reach output saturation. When this happens, the integrated errors in equation (2.22) will keep on increasing and will cause the output to continue to output the maximum value even after the set point is reached. The solution to this is anti-windup. One method of anti-windup is conditional integration in which the integral part is paused when the output saturation is reached [14].

2.3.2 PID - tuning using Ziegler-Nichols method

The Ziegler-Nichols method for tuning a PID is a experimental approach to tuning P, PI and PID controllers. It is done by setting the integral gain K_I and the derivative gain K_D to 0 and then increase the proportional gain K_P until the system has stable and consistent oscillations. The gain when this is reached is called the ultimate gain K_u. One can then measure the oscillation period T_u and use that together with K_u to determine the other parameters according to the table shown below [15].

Table 2.1: The scaling used for the different parameters. This is a very gentle approach to the Zeigler-Nichols method

Control Type	proportional gain[K_p]	integral gain[K_I]	derivative gain[K_D]
No Overshoot	$0.2K_u$	$\frac{0.2K_u}{T_u}$	$0.066K_uT_u$

For this thesis work only the most careful setting aimed at reducing overshoot completely is used. Zeigler-Nichols, however, can often generate overshoots even with these settings, which can result in further tuning being necessary.

2.3.3 Fuzzy Logic

Fuzzy logic is a multi-valued form of logic that can have values between the usual 1 for true and 0 for false. This makes fuzzy logic able to handle partial truths, making it very flexible and an accurate decision-making method. The fuzzy controller consists of five steps as seen in the figure below.

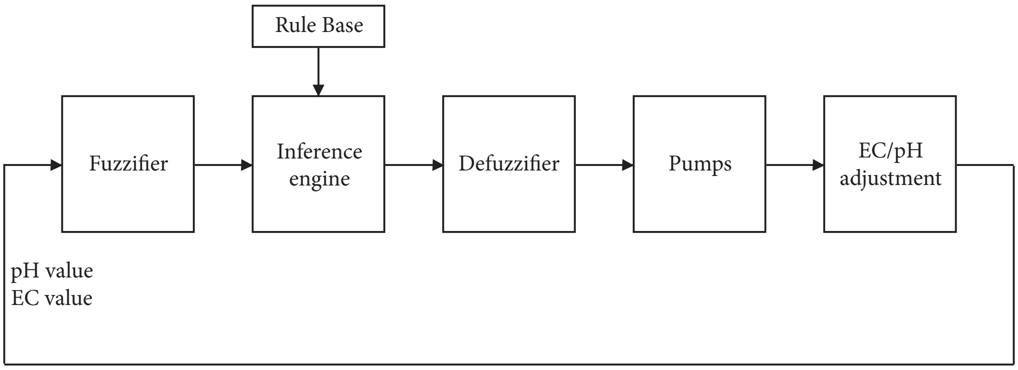


Figure 2.1: Fuzzy controller in a hydroponic system

In fuzzy logic, the input and output ranges have to be defined. These are chosen to represent all the different input and output scenarios. The inputs and outputs are then put into membership functions to represent what action to take depending on the input. The system uses a set of different rules to make its decisions. These fuzzy rules combined with the membership functions affect the decisions and output of the system. The last process is called defuzzification and this process converts the fuzzy decisions into actual values.

2.3.4 Pulse-Width Modulation Control

Pulse-width modulation(PWM) refers to analog-like control through digital means. The way this is achieved here is by turning on the max output of the motor with a certain duty cycle which results in pulses of the max output. Doing this at a high frequency replicates the the behaviour of a analog controller. This is a good alternative when analog control is not available, as is the case when a Raspberry Pi[16] is used. The behavior can be described by

$$y = D \cdot y_{max} + (1 - D) \cdot y_{min} \tag{2.23}$$

where D is the duty cycle, y_{max} is the maximum output of the motor, y_{min} is the minimum output of the motor and y is the averaged output of the motor. Typically y_{min} is equal to zero, resulting in $y = D \cdot y_{max}$ as the final equation.

2.4 Sensors

2.4.1 pH Sensor

The sensor used for measuring pH in this work uses two electrodes, one measuring electrode and one reference electrode. The reference electrode uses a neutral solution with a pH of 7 while the measuring electrode is submerged in the liquid where the pH is measured. The sensor then measures the difference in voltage between the hydrogen ions in the solution and the reference node. When these are compared, the pH of the solution can be calculated [17].

2.4.2 EC Sensor

The sensor used is a two-pole sensor. It works by applying an alternating voltage between the two electrodes. The amount of current that is able to travel between the electrodes is roughly proportional to the salt concentration in the solution. This type of sensor has a limited range and is affected by salts in the water. However, because it is inexpensive it is often used in hydroponics[18].

2.4.3 Temperature Sensor

A temperature sensor consists of a diode often connected to a bipolar transistor. When the temperature increases, the voltage over the diode also increases. Usually this is connected to an integrated circuit that converts the voltage to a temperature as well as adjusts any non-linearities that may be present [19].

2.4.4 Hygrometer

A hygrometer measures the humidity in the air. It can measure both absolute humidity or relative humidity depending on what kind of sensor is being used.

The absolute humidity is defined as the mass of water vapor in the air divided the volume of air [20]. It can be expressed as

$$AB = \frac{m_w}{v}, \tag{2.24}$$

where AB is the absolute humidity in grams over cubic meter, m_w is the mass of water vapor in grams and, v is the volume of the air being measured in cubic meters [20]. The saturation humidity is the maximum possible water concentration in the air and is defined by

$$SH = \frac{m_{ws}}{v} \tag{2.25}$$

where SH is the saturation humidity in grams over cubic meter, m_{ws} is the mass of the water vapor at saturation and v is the volume of air being measured.
Relative humidity is another measurement that is more commonly used. Relative humidity is the the ratio of moisture content of the air over the maximum possible moisture content of the air. It is therefore a percentage and can be defined in two ways, i.e

$$RH = \frac{P_v}{P_s} \cdot 100 = \frac{AB}{SH}, \tag{2.26}$$

where RH is the relative humidity in percent, P_v is the partial pressure of moisture in air in Bar and P_s is the saturated pressure of moist air in Bar [20]. P_v and P_v need to be at the same temperature. The relative humidity can also be calculated from Equation (2.24) and (2.25).

A capacitive hygrometer measures relative humidity by measuring the capacitance between two metal plates. Between these plates is a dielectric material, typically with a dielectric constant of 2 to 15. Water vapor has a dielectric constant of about 80 at room temperature, which results in an increase in capacitance when the sensor absorbs water vapor [21]. The relationship between capacitance and relative humidity is not linear and varies depending on temperature, pressure, and the materials used [22].

3

Method

3.1 System

The system consists of four pumps, an Arduino, a Raspberry Pi, and multiple kinds of sensors. These components will briefly be explained and motivated. A simplified illustration of the system is shown in Figure 3.1.

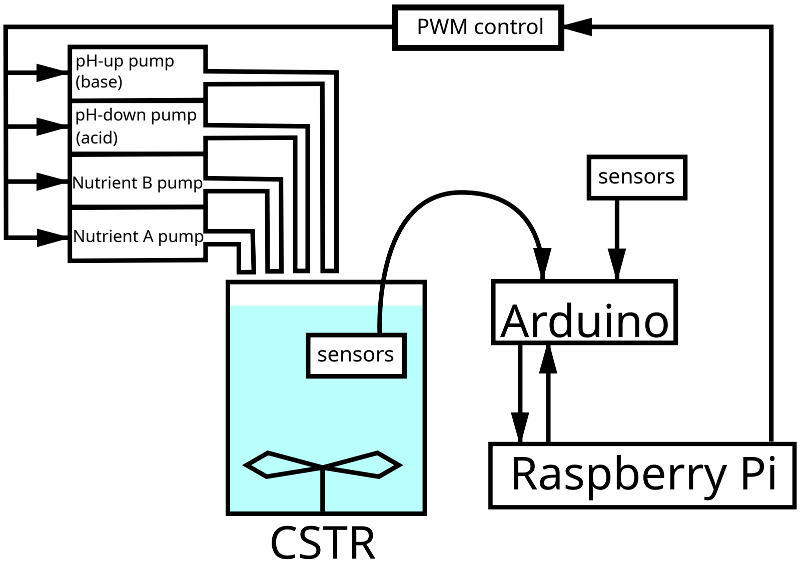


Figure 3.1: A simplified version of the system. A more realistic one would replace the CSTR with the hydroponic system

3.1.1 Watertank

The hydroponic growing system consists of Growpipes. This allows for vertical growth of plants with only water as growing medium. A pump is used to pump the water to the top of the system so that it can pass through all the plants in the system. A water tank is used where the water is collected and the pump is placed. For the purpose of this project, the whole system can be viewed as a continuously stirred tank reactor (CSTR) with a mixing delay of 8 seconds, the reason for this is that when the water returns to the tank, it also mixes the solution.

3.1.2 Microcontrollers

There are two microcontrollers. An Arduino that handles sensor signals and a Raspberry Pi used for calculations and to control the pumps. The Arduino acts as an analog-to-digital converter (ADC) since The Raspberry Pi only has digital GPIO (general-purpose input/output) pins. Digital GPIO pins can only transmit and receive digital signals. For simplicity, all sensor measurements are done by the Arduino even if some of them use digital signals. This is then sent to the Raspberry Pi on request from the Raspberry Pi. The Raspberry Pi includes two control systems, one for EC and one for pH.

3.1.3 3D-printed parts

A case was created in Fusion 360 and then 3D-printed. The case was made to hold the microcontrollers and sensors in place. It was made in two parts, a top and a bottom with space for all the necessary ports and sensors, as seen in Figures 3.2 and 3.3.

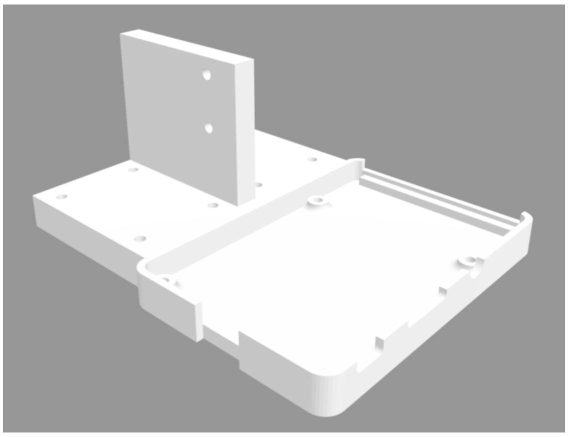


Figure 3.2: Base of microcontroller case

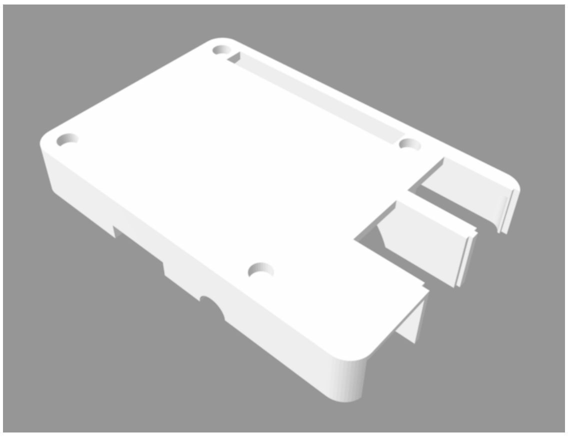


Figure 3.3: Top of microcontroller case

A float was also created in Fusion 360 and then 3D-printed. This float was created for the pH, EC and water temperature sensors in order to keep all sensitive parts of the sensors above water.

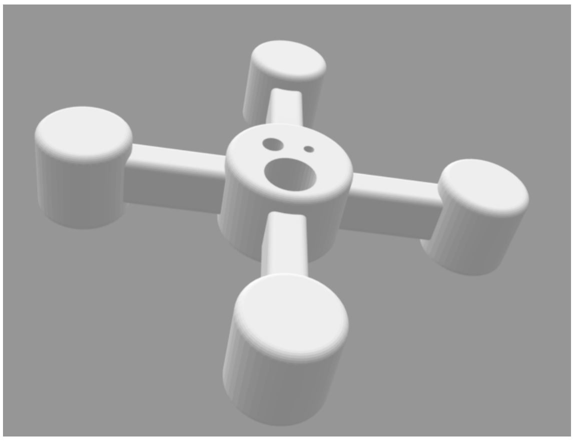


Figure 3.4: Float made for sensors

3.1.4 Hygrometer

The hygrometer measures the humidity, where the system is placed, for monitoring purposes. The system does not control humidity, which therefore must be manually adjusted by the user. The model used in this project is a capactive Hygrometer/Thermometer with model number DFRobot-DHT22 and was chosen for its simplicity with digital output see Figure (3.5).

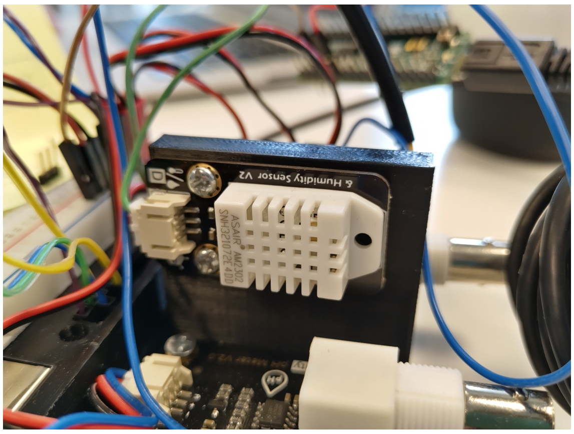


Figure 3.5: DFRobot-DHT22 sensor used in the project

3.1.5 Thermometers

There are two thermometers being used in the system. One measures the air temperature in the room the system is placed in to make sure the ambient temperature is not too high for the plants. However, this is not controlled by the system and must be manually managed by the user. The other thermometer measures the water temperature and is used by the EC- and pH pumps to make corrections to the measurements taken by those sensors. The model used is the previously mentioned DFRobot-DHT22 for air temperature shown in Figure 3.5 and for water temperature the DFRobot-KIT0021 shown in Figure 3.6 was chosen. Both were chosen because of their digital output as well as being commonly used in similar projects which would simplify troubleshooting.

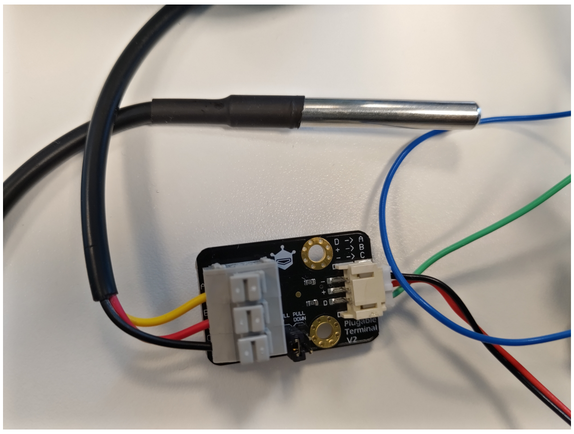


Figure 3.6: DFRobot-KIT0021 sensor used in the project

3.1.6 EC-sensor

The EC sensor measures the electrical conductivity of the water. This is then converted to an analog voltage value from a circuit, which is then fed to the Arduino. Which converts the analog voltage to a digital value with the unit mS/cm. The sensor used is DFRobot-DFR0300, which was chosen due to the included control card. The sensor is shown in Figure 3.7.

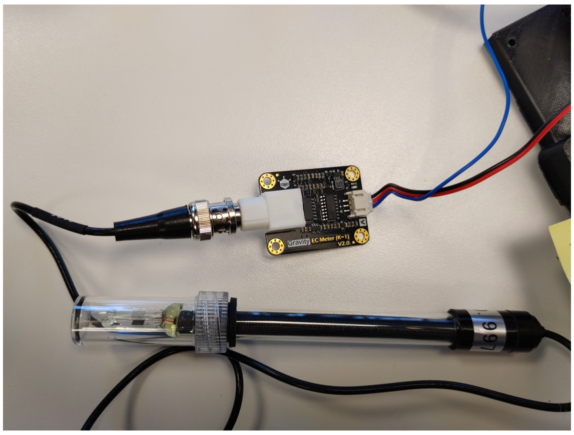


Figure 3.7: DFRobot-DFR0300 sensor used in the project

3.1.7 pH-sensor

The pH sensor measures the activity of hydrogen ions in the water. This is then converted to an analog value from a circuit, which is then fed to the Arduino, which converts the analog voltage to a digital value. The sensor used is DFRobot-SEN0169-V2, which was chosen due to the included control card and for its capability to be submerged continuously. This sensor is shown in Figure 3.8.

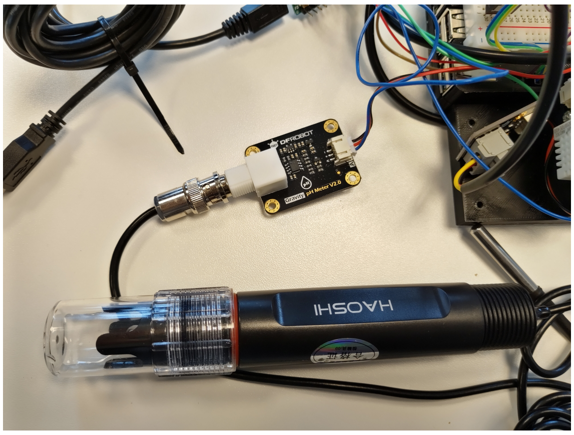


Figure 3.8: DFRobot-SEN0169-V2 sensor used in the project

3.1.8 Pumps

The pumps are of the peristaltic model, where the pump itself never touches the fluid. These four pumps are used to pump phosphoric acid (pH down), potassium hydroxide (pH up), and two types of nutrient solution, when needed into the tank of the system. The pumps are connected to the Raspberry Pi and a separate power source. The Raspberry Pi controls 4 transistors that allow for on/off of the pumps as shown in Figure 3.10, to achieve analog-like behavior they were controlled by pulse width modulation (PWM). The pump chosen was Adafruit-3910. A 5-6 V pump with a maximum output of 100ml/min. The power supply (PSU) used for the pumps is 5 V, 2.1 A, which means that it can power two pumps at maximum speed at a time under optimal conditions, which is all that is required since no more than two pumps will be running at once. This pump is shown in Figure 3.9.

Figure 3.9: Adafruit-3910 pump used in the project

The circuitry for the pumps is shown in Figure 3.10.

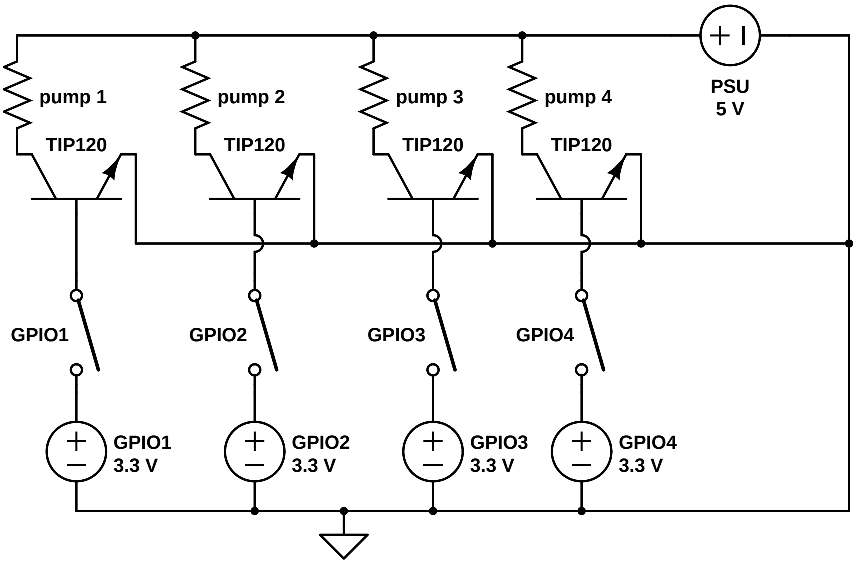


Figure 3.10: Circuit describing the control of the pumps with General-Purpose Input/Output(GPIO) pins on the Raspberry Pi

3.1.9 Disturbances between EC sensor and pH sensor

The EC-meter using a two-pole solution to take measurements results in disturbances for the pH-meter. Because of this, the pH meter can't be used when the EC meter is connected and has power. As the software does not need to actively measure both sensors at the same time, a relay was placed on the power to the EC-meter being controlled by the Raspberry Pi activating it, before taking measurements and disabling it when finished.

3.2 Titration Comparison With Model of PH

The model described in Section 2.1 will be compared with data from a titration experiment conducted with the help of the system described in Section 3.1. This was conducted by pumping phosphoric acid into a tank of 20 L of tap water until the solution reached a pH of 3. Another pump would then add potassium hydroxide at a flow-rate of 0.056 ml/s until a pH of 11 is reached. The data is logged and then compared to the pH curve resulting from the equations in Section 2.1 to determine if the model is a good representation of pH for solutions containing triprotic acids. The Simulink-version of the model based on the theory of Section 2.1 is presented in Figure 3.11.

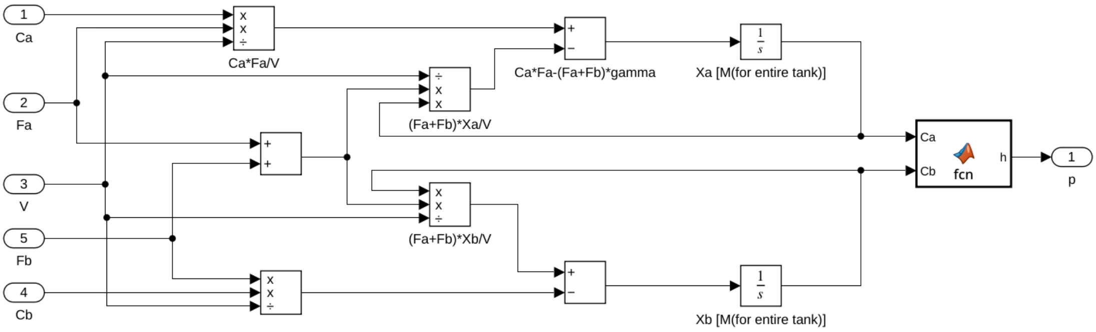


Figure 3.11: Simulink model of pH

Figure 3.12 shows the entire control system with the pH process given by the model shown in Figure 3.11.

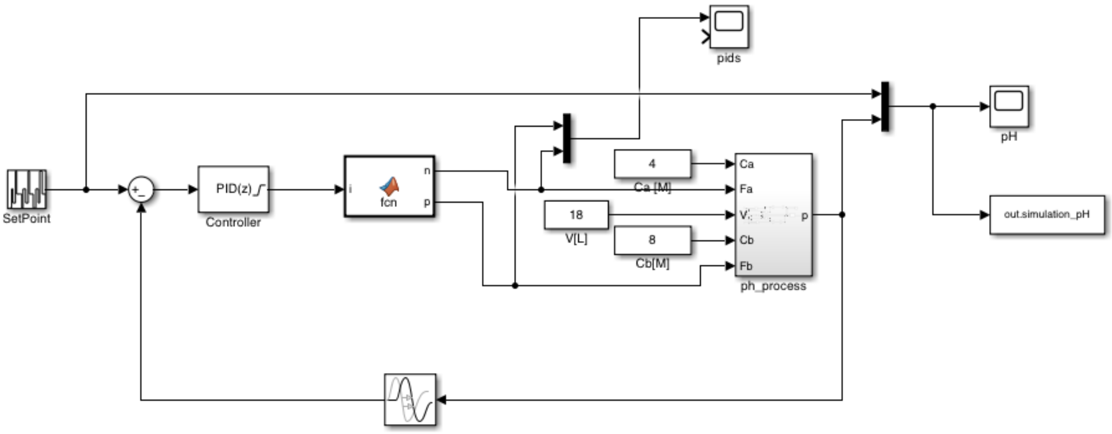


Figure 3.12: Simulink model of the pH-control using PID-controller. The system model for Fuzzy control looks the same but uses a Fuzzy controller instead of a PID controller

3.3 Creation of model for EC

The model described for EC was created with data from the titration performed by the system described in Section 3.1. This was done by pumping nutrient solution A and nutrient solution B in equal parts at a rate of 0.056 ml/s into a 20 L tank of water until the solution reaches an EC value of 3 mS/s. The data is logged and then used to create a model where constants where determined manually. To verify that the model works for different tank volumes, a second experiment was conducted in the same way. The only difference was the tank volume, which was changed to 5 L. The expected result was calculated by the model and compared to the measurements. The Simulink-version of the model is presented in Figure 3.13.

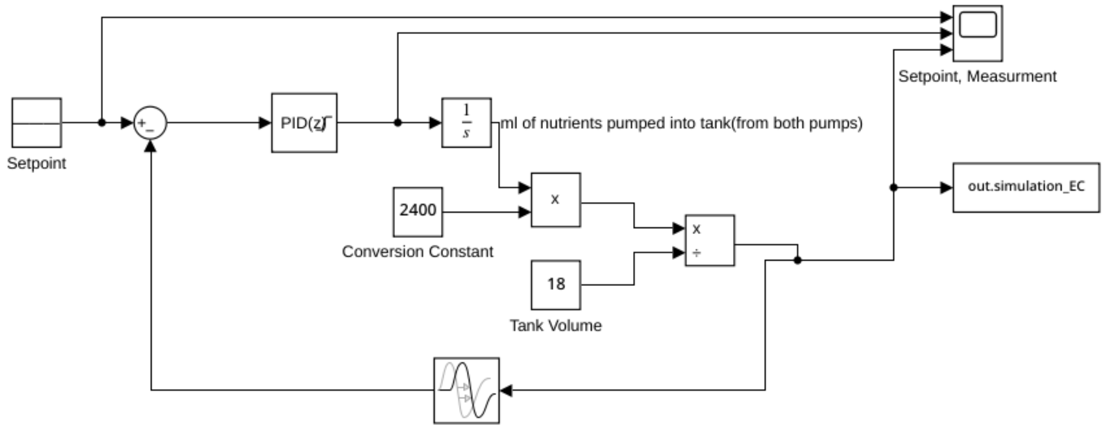


Figure 3.13: Simulink model of the EC-control, the model for a Fuzzy control looks the same but uses a Fuzzy controller instead of a PID controller

3.4 Pump Calibration

As mentioned the pumps are controlled by PWM. The reason for this is the Raspberry Pis limitation to only use digital outputs. One issue with this is that the relationship between PWM used and the flow rate of the pump is not one to one. To handle this the output of the pumps needs to be measured and compared to a the output required of the pump. To do this, all pumps were tested individually to make sure there was no big difference between them. The values decided on were 20%, 40%, 60%, 80% and 100% of maximal output. The pump was then allowed to pump water into a glass that was weighed, the percentage of max was varied until the desired amount of water was reached. When this had been done for all pumps and percentages the values were compared and the rest of the values from 20%-100% were interpolated from the data gathered.

3.5 PID Design

A PID with anti-windup was developed for both the EC- and pH models using the Ziegler-Nichols method in Simulink, which was then also tweaked to perform better. The tweaking was especially important for the pH because of the rate of change of the pH at different values of pH. The resulting control systems were then tested in the live system and tweaked according to the results.

3.6 Fuzzy-logic Design

Fuzzy logic has many different applications and is quite often used in hydroponics. Fuzzy logic must be specifically designed for the system and its purpose. Due to this, it has its limitations, but usually performs very well at the task at hand. This system has one input and one output and is a Mamdani fuzzy interference system that uses the mean of the maximum to take its decisions. The fuzzy systems were first created using The Fuzzy Logic Toolbox in Simulink and adjusted to better suit its purpose. The simulated system was then tested and adjusted after the test results. The model can be seen in Figure 3.14.

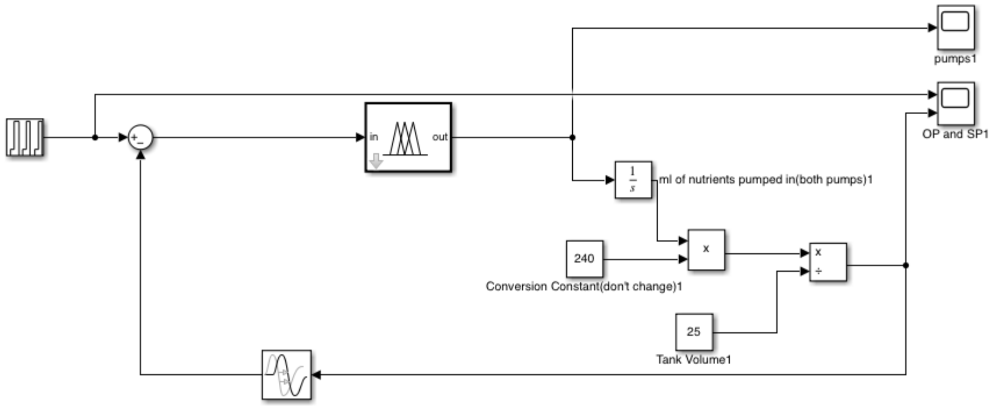


Figure 3.14: Simulink for Fuzzy-EC-controller

3.7 Second Verification of pH-Model

A certain behavior was observed in the pH-model, where the change in pH became slower over time. To verify this, an additional experiment was performed. This time, both the pH-up and the pH-down pumps were connected and the set point shifted between 7 and 7.5 to observe whether continuous application of acid and base would result in slower reactions.

3.8 Comparison Between PID and Fuzzy Logic Control

To establish a fair comparison of performance between the PID and the Fuzzy Logic controller, an identical test was performed on both systems. The test for EC was simply giving a setpoint for them to reach and observe the time and accuracy of the systems. For pH, a more thorough test was needed to observe how the systems could handle both raising and lowering the pH. Another important aspect was how well the system could handle the pH nonlinearities and equivalence points. The test was constructed by setting a couple of different pH-setpoints for the systems to try to achieve in a given amount of time per setpoint.

4

Results

4.1 Model for PH

The titration experiment described in Section 3.2 resulted in Figure 4.1. A close correlation can be observed between a pH of 3 to 9. Measurements from pH values above 9 deviate by around 1.7 from the model. This implies that the model can be used reliably between a pH of 3 and 9 and in this specific case the model can be used for experimentation with different control systems. This experiment does not show some of the issues related to rapid changes in pH at the start of simulation, where the concentration of acid and base are close to zero, which will become apparent in a later experiment.

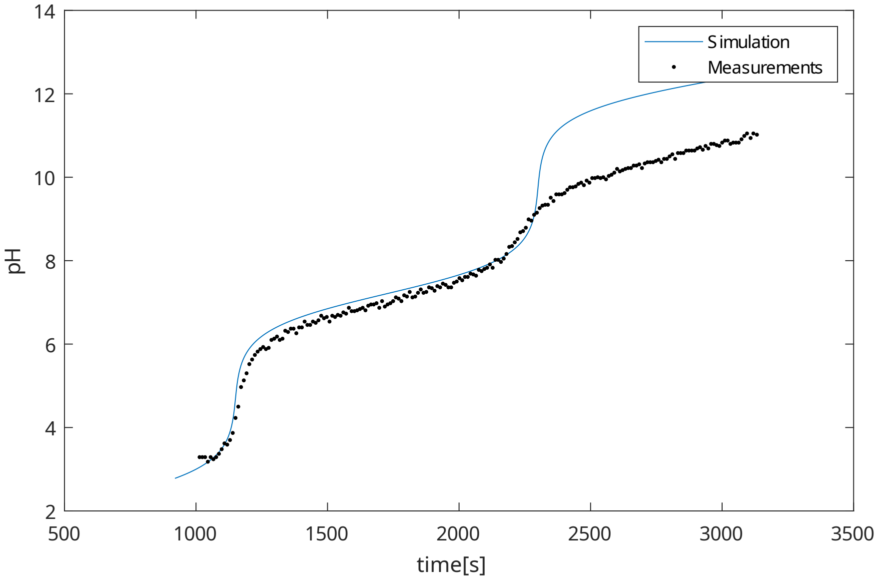


Figure 4.1: The model simulation compared to measurements. Shows Titration with 20% KOH and 80 % H_2O is distributed at a rate of 0.056 ml/s

4.2 Model for EC

The EC model is linear and can be described by

$$EC = \frac{V_N \cdot 2400}{V(0) + V_{N(t)}} \tag{4.1}$$

where EC is the electrical conductivity in mS/s, L is the amount of nutrients in the tank in liters, and $V(0) + V_{N(t)}$ is the total tank volume in liters. The constant 2400 was determined experimentally as described in Section 3.3. The model compared to the measurements is shown in Figure 4.2.

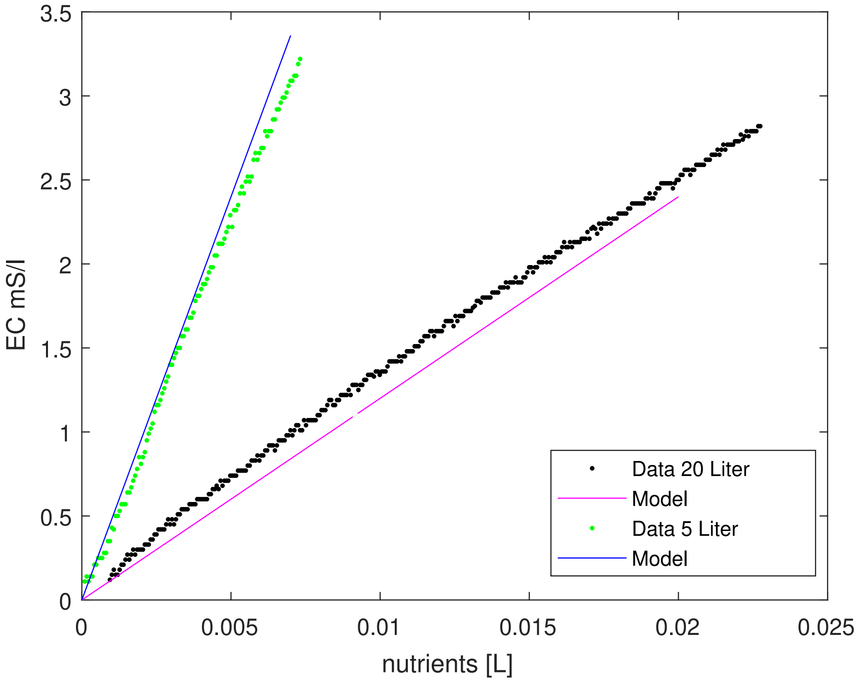


Figure 4.2: The data used for model parameterization and model verification

4.3 Pump Calibration

The pumps' output was measured as explained in Section 3.4. The resulting values are shown in Table 4.1.

Table 4.1: Output from the pumps at target percentages

Duty Cycle [%]	Pump 37 Actual [%]	Pump 38 Actual [%]	Pump 32 Actual [%]	Pump 35 Actual [%]	Average [%]	Pump Speed [mL/s]
20	26	26	26	28	26.5	0.15
40	38	32	35	36	35.25	0.30
60	48	45	45	45	45.75	0.45
80	60	60	62	61	60.75	0.60
100	100	100	100	100	100	0.75

The largest difference between values were 6% of max output. Since the maximum difference in output was 0.018 mL/s, an average of all pumps was determined acceptable to use to determine the final factor to be used when scaling the pump speed. From this average, the other remaining values were interpolated as shown in Figure 4.3. This resulted in a look up table of 80 values with a factor for each whole percentage of max speed.

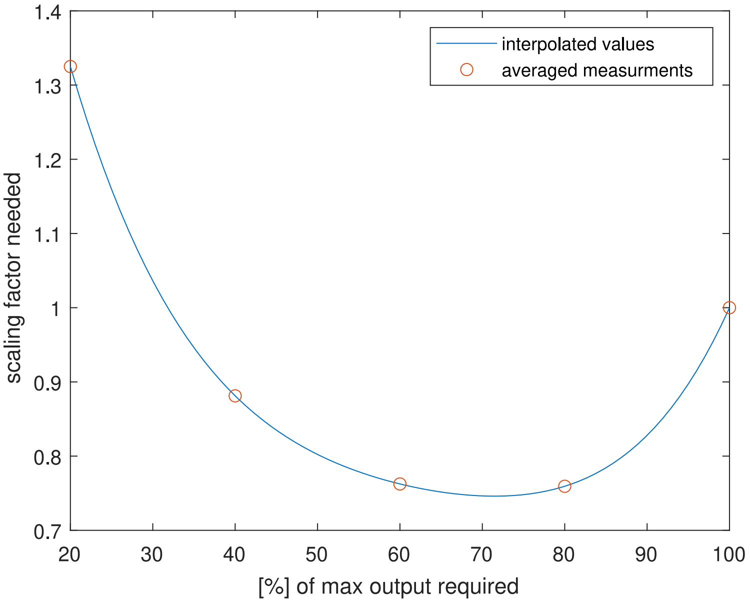


Figure 4.3: The scaling factor needed to reach a certain percentage of max output for the pumps

It was also discovered that 20% of the maximum output was the minimum the pumps could produce before they would stall and all settings were adjusted accordingly. This is also the reason why the graph goes from 20%-100%.

4.4 Fuzzy Logic

4.4.1 pH

This fuzzy system is designed to be rather slow and precise rather than fast. This is due to the pH error usually being small. The only time when the error can be large is before the first adjustment.

The membership function in Figure 4.4 shows that the pH input error is between high and low compared with the set pH-value. The x-axis displays the pH error in both directions and the y-axis displays the degree of membership.

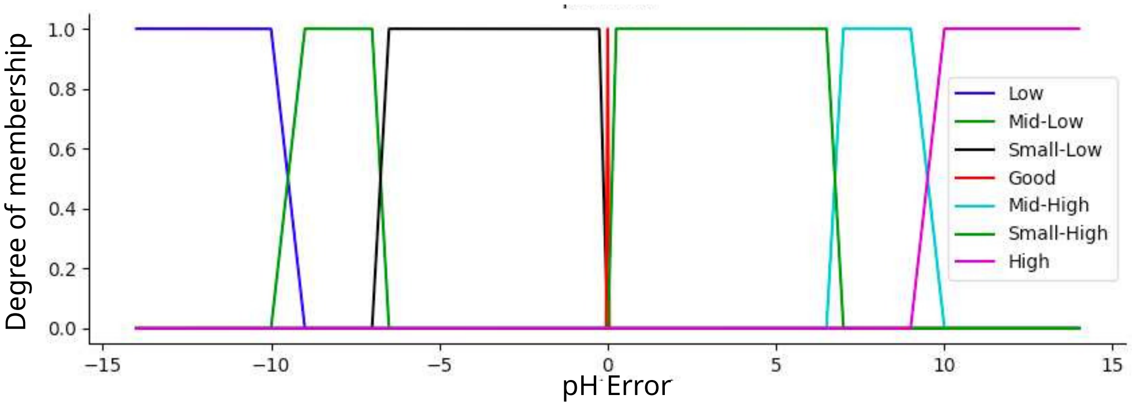


Figure 4.4: The pH input error from the system, with degrees depending on how big the error is compared to the set value

Figure 4.5 shows the output of the fuzzy logic decision. This ranges from negative full (NF) to positive full (PF) and the x-axis shows the pump speed in L/s.

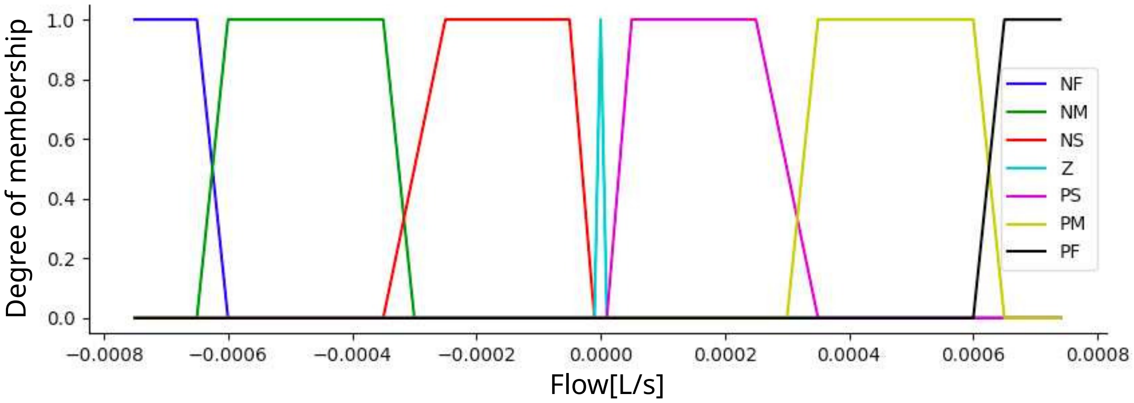
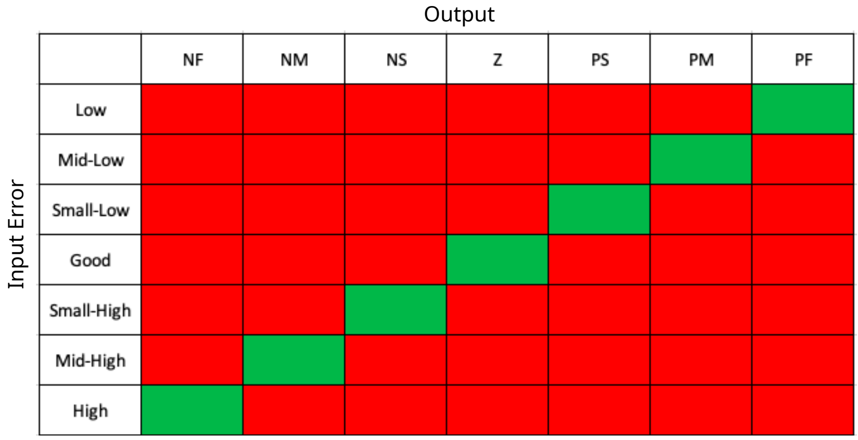


Figure 4.5: The output from the Fuzzy-logic system where the negative values represent the pump flow for acid and positive values represent the pump flow for base

The membership functions in Figure 4.4 and 4.5 together with a set of rules showed in Figure 4.6 creates the fuzzy interference system. The input pH error is matched with the rule table and this table decides the flow of either acid or base. The degree of membership decides to what degree the value belongs to a membership function, so if a value is between two functions it matches with two rules to different degrees. An example of this would be if the pH error is -8. This places it in the Mid-low region of the membership function and this would cause positive mid (PM) to be activated and the pump would work between 0.3 and 0.65 mL/s.



Output

Input Error

	NF	NM	NS	Z	PS	PM	PF
Low	🟥	🟥	🟥	🟥	🟥	🟥	🟩
Mid-Low	🟥	🟥	🟥	🟥	🟥	🟩	🟥
Small-Low	🟥	🟥	🟥	🟥	🟩	🟥	🟥
Good	🟥	🟥	🟥	🟩	🟥	🟥	🟥
Small-High	🟥	🟥	🟩	🟥	🟥	🟥	🟥
Mid-High	🟥	🟩	🟥	🟥	🟥	🟥	🟥
High	🟩	🟥	🟥	🟥	🟥	🟥	🟥

Figure 4.6: The set rules for pH in the Fuzzy-controller

The membership function in Figure 4.4 shows the input error is between high and low. Figure 4.7 displays a comparison between the simulated fuzzy system and the actual performance of the system. The strange behavior in the measurement curve between 500 and 850 *s* is due to lost measurement values.

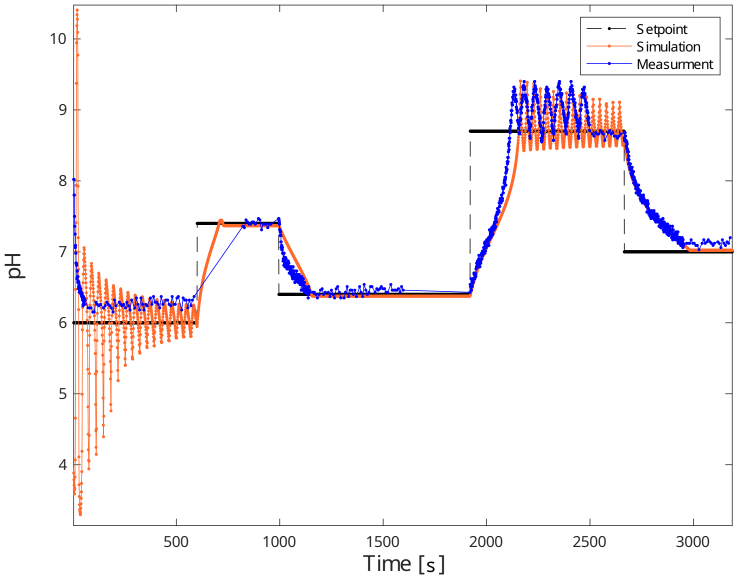


Figure 4.7: Comparison between simulation and test for pH control using fuzzy-logic for different set points.

4.4.2 EC

The membership function in Figure 4.8 shows the input error between low and good. The EC value is only regulated if it is low, since nutrients are added and never removed from the water. The X-axis in Figure 4.8 and 4.9 is scaled with 10^4 due to the Python extension not being able to handle integers and decimals.

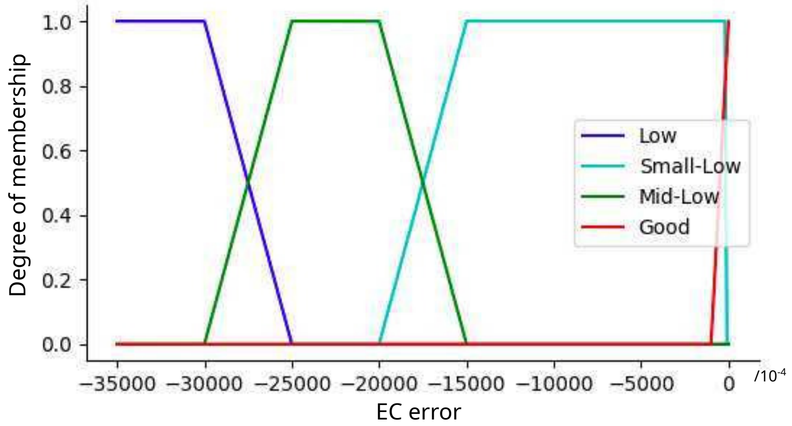


Figure 4.8: The EC input error from the system, with degrees depending on how big the error is compared to the set value

Figure 4.9 shows the output from the fuzzy logic decision. The output ranges from zero (Z) to positive full (PF) and the x-axis shows the pump speed in L/s.

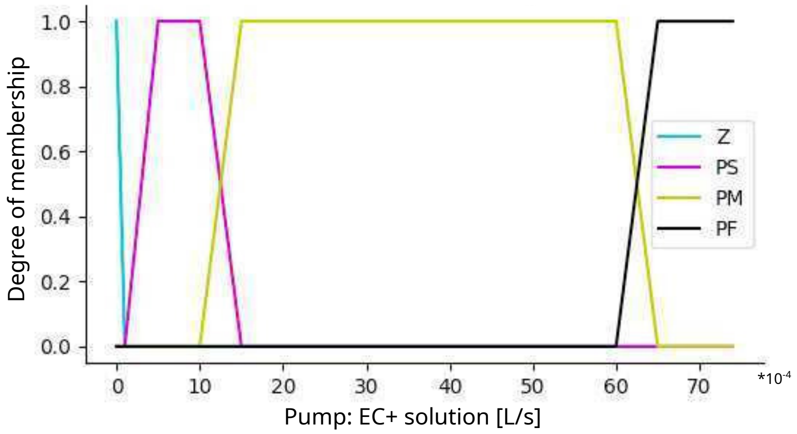
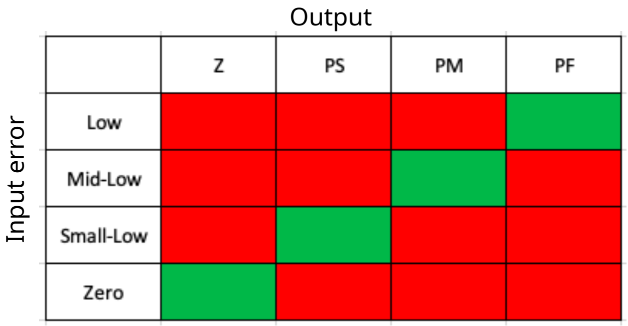


Figure 4.9: Input and output from Fuzzy-logic

These membership functions together with a set of rules showed in 4.10 creates the fuzzy interference system.



	Z	PS	PM	PF
Low	🟥	🟥	🟥	🟩
Mid-Low	🟥	🟥	🟩	🟥
Small-Low	🟥	🟩	🟥	🟥
Zero	🟩	🟥	🟥	🟥

Figure 4.10: Rules for Fuzzy-controller

Figure 4.11 displays a comparison between the simulated Fuzzy system and the actual performance of the system.

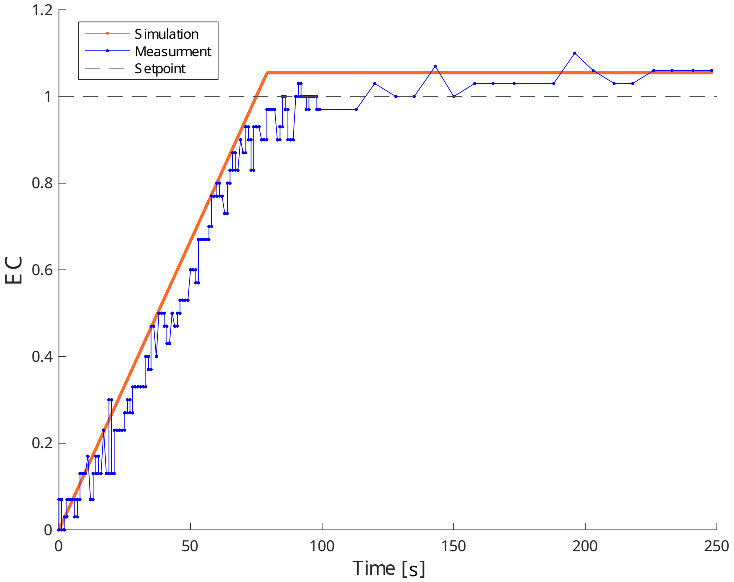


Figure 4.11: Comparison between simulation and test for EC control using Fuzzy-logic at a setpoint of 1

4.5 PID-controller

4.5.1 pH

Parameters for tuning the PID controller for pH at different stages are shown in the table below,

Table 4.2: The resulting gains for the PID tuning

Tuning Method	K_p	K_i	K_d
Zeigler-Nichols	$2 \cdot 10^{-4}$	$5.7 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$
Tweaked Zeigler-Nichols	$2 \cdot 10^{-4}$	10^{-7}	10^{-7}
Tweaked Real situation testing	$2.5 \cdot 10^{-4}$	10^{-7}	$4 \cdot 10^{-7}$

There is a small difference between the different versions, where the main difference is between the parameters K_i and K_d. After tuning these parameters, both became smaller. A comparison was made between the simulation and the real-life system, which can be seen in Figure 4.12.

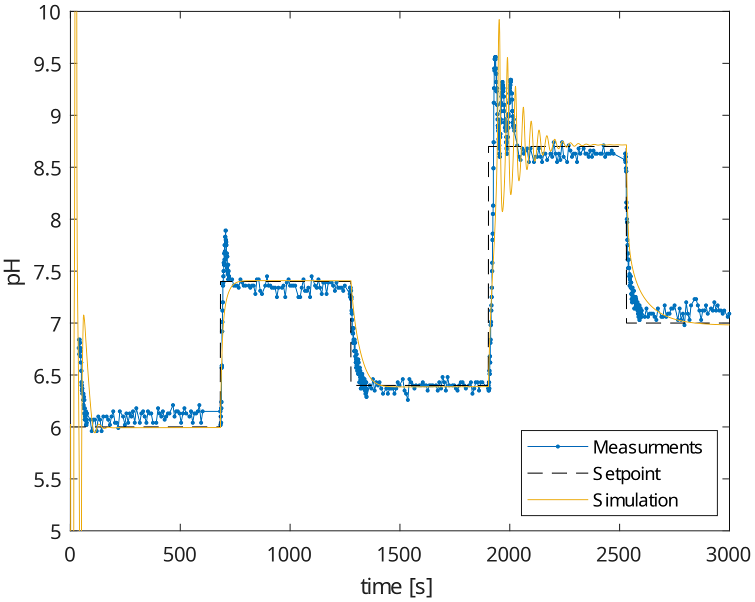


Figure 4.12: Comparison between Simulated and real life PID for EC

In Figure 4.12 the start of the simulation shows large fluctuations, which will be discussed in a later section.

4.5.2 EC

The parameters from tuning the PID controller for EC at different stages are shown in the table below.

Tuning Method	K_p	K_i	K_d
Zeigler-Nichols	$4 \cdot 10^{-4}$	$1.1 \cdot 10^{-5}$	$9.2 \cdot 10^{-4}$
Tweaked Zeigler-Nichols	$4 \cdot 10^{-4}$	$5 \cdot 10^{-6}$	$2.64 \cdot 10^{-3}$
Tweaked Real situation testing	10^{-3}	3.3^{-2}	$4 \cdot 10^{-7}$

The largest tuning differences were from going to real situation testing where all parameters needed quite large adjustments. A comparison was made between the simulation and real-life system which can be seen in Figure 4.13.

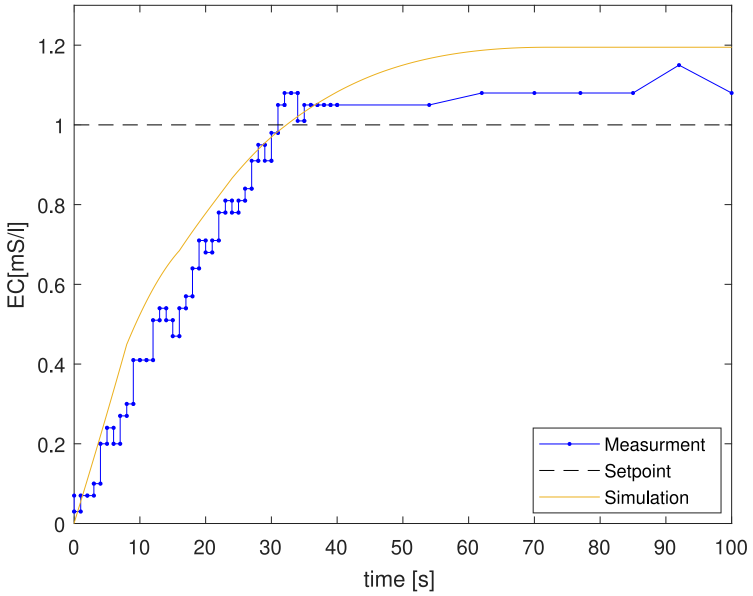


Figure 4.13: Comparison between Simulated and real life PID for EC

4.6 Comparison between PID- and Fuzzy Controller

4.6.1 pH

Fuzzy logic and PID control systems were compared by using the same setpoints resulting in Figures 4.14, 4.15 and 4.16.

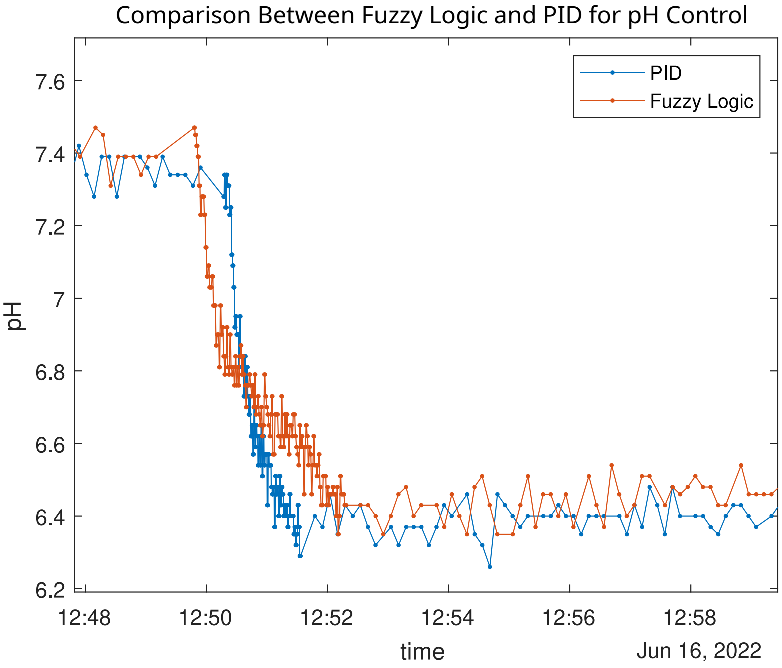


Figure 4.14: Comparison between fuzzy and PID control for a setpoint of pH 6.5

The first setpoint of 6.5 in Figure 4.14 shows similar results for fuzzy- and PID control. PID is faster with a drop time of 80 seconds, while fuzzy control shows a droptime of 120 seconds.

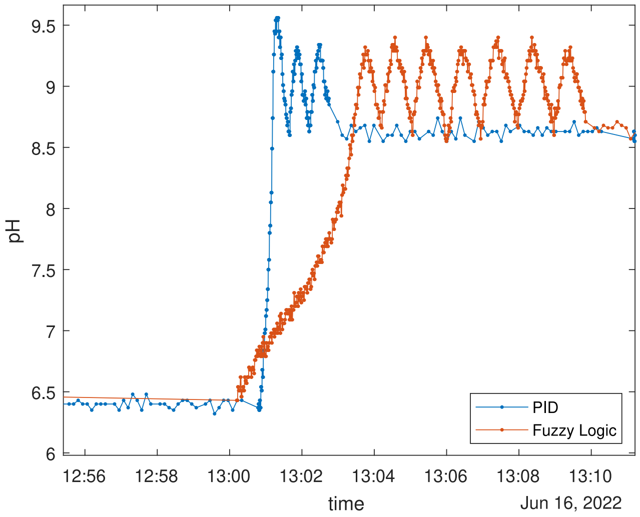


Figure 4.15: Comparison between fuzzy and PID control for pH 9

The second setpoint of 9 in Figure 4.15 the results for fuzzy- and PID control. PID is faster with a rise time of 40 seconds while fuzzy control shows a rise time of 210 seconds. Both methods suffer from oscillations, but where the PID control manages to reach the setpoint after 3 oscillations. Fuzzy control has stable oscillations and doesn't reach a stable setpoint value at all for the 10 minutes the control system was running. The reason for these oscillations is that 9 is an equivalence point for phosphoric acid, which means that the change in pH is more rapid around this point.

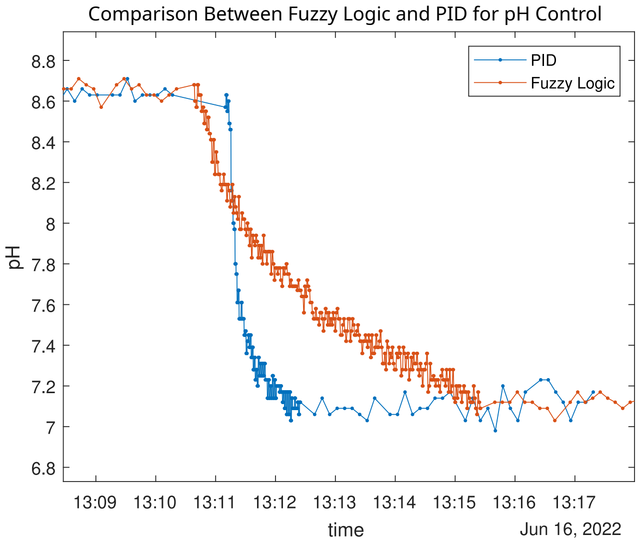


Figure 4.16: Comparison between fuzzy and PID control for a setpoint of pH 7

Figure 4.16 shows the results for the last set point of pH 7. Once again PID control shows a faster drop time of about 30 seconds while fuzzy logic show a drop time of 240 seconds. Both are stable and exhibit no oscillations.

4.6.2 EC

The Fuzzy logic and PID controllers were compared by setting a setpoint of 1 as seen in Figure 4.17. The PID performed faster with a rise time around 40 seconds whereas the fuzzy logic system had a rise time of around 90 seconds. Both systems overshoot the setpoint. The PID stabilized around 1.14 and the fuzzy control system stabilized at around 1.06.

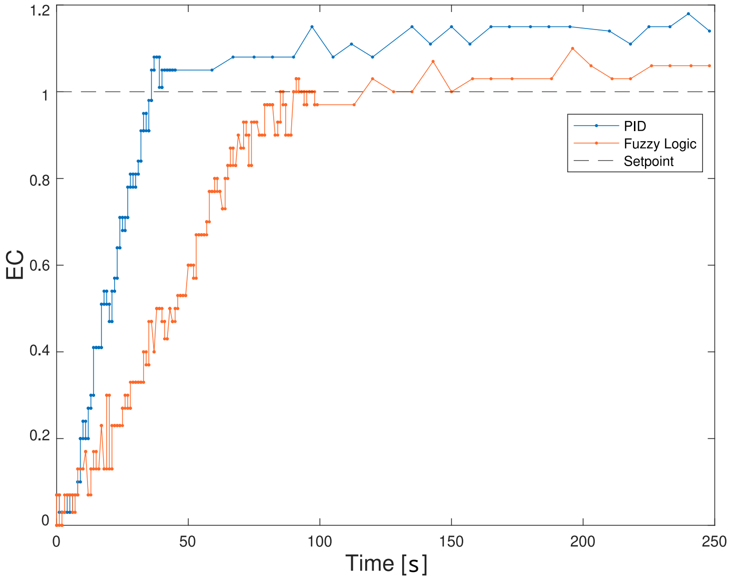


Figure 4.17: Comparison between fuzzy and PID control for a setpoint of 1 for EC

4.7 Change in amount of acid/base needed to reach target pH based on acid and base already added to the solution

A test was carried out according to Section 3.7. The goal was to figure out if integrating acid and base alternatingly into a water tank would need the same amount of acid and base each time to reach the target values.

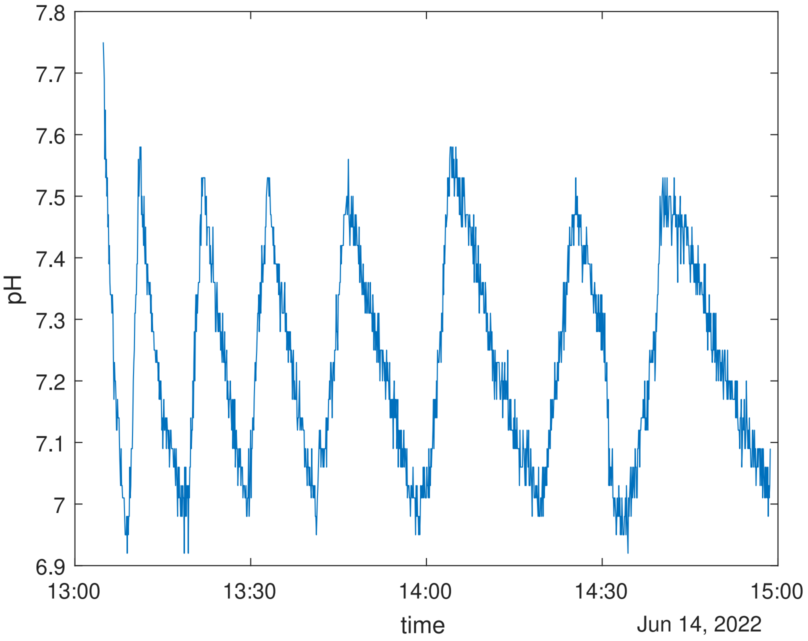


Figure 4.18: Change in acid/base needed to reach a specific pH value based on the previous amount of acid and base added

The results are also shown in the table below where period refers to the period which starts at pH 7 and ends the next time it reaches pH 7 again. and period time is the time it takes for this to happen. the table is based on the plot.

period	period time [min]
1	10
2	10.5
3	11.5
4	16
5	20
6	15
7	25

The results show an increase in time needed (with constant flow) to increase and decrease pH depending on how much acid and base has been added. This means that the resulting reaction from the acid and base slowed the systems reaction speed. The only exception for this is period 6.

5

Discussion

5.1 Enviromental aspects

The UN has 17 sustainability goals, many of which vertical farms can be a part of [23]. Goal 11 includes sustainable cities. Vertical farms can help with this by cutting out shipping on the large scale. Goal 12 is related to responsible production and consumption. This thesis project can help with this by having a cheaper system for pH and EC regulation, which enables industrial indoor farmers to have multiple separated systems. This, in turn, can be used to avoid diseases from the water, which can eliminate waste. Goal 13 is related to greenhouse gases. A large problem is that a lot of farmland is created by removing the rain forest. Not only does this increase the greenhouse gases but it also reduces the biodiversity in the area [24]. Increasing the biodiversity is a part of Goal 15. By moving farmland to a vertical setting, less land would need to be used since vertical farming relies more on volume to grow instead of area like in traditional farming.

Goal 7 is related to energy and since the method of growing indoors shifts the need for a lot of water to a need for more electricity, mainly for growing lamps, this is a risk. The lamps are not a part of this project, but they are a problem with these systems if non-sustainable sources for electricity are used.

A study by World Wildlife Fund (WWF) showed that conventional farming is currently the method with the lowest environmental impact. This is with current electrical sources, natural resource availability, and technological efficiency. However, if the electricity used for the hydroponic farms is sourced from renewable energy sources then vertical hydroponic farms would have a lower impact on the environment. Most of the electricity used is for lighting. Therefore, more efficient lighting or the possibility of using natural light resources would drastically reduce the electricity need for these farms [25]. In extreme conditions hydroponics has the possibility to use only 10% of the water used in more traditional farming due to the fact that the water not obtained by the plants is recycled in the system and not wasted [26].

5.2 PID vs Fuzzy pH

Overall, PID performs better for pH regulation. This could be due to more aggressive tuning on the PID controller compared to the Fuzzy controller. In the instance where the set point of 6.5 pH is chosen, shown in Figure 4.14, the time needed to reach the set point differ with about 50 seconds, which is further increased in the two tests for Figure 4.15 and Figure 4.16, where the time difference was 9 minutes and 3 minutes, respectively. It could be argued whether this really matters, as rapid change is not the most important aspect of a growing system, but rather stability of pH and frugality of pH-up and pH-down solutions. On both of these aspects the results are similar. However, for a set point of 7 and 6.5 both control systems perform similarly, but for a set point of 9 the PID control system causes 1.5 oscillations before settling and the Fuzzy control system causes 6 oscillations before settling. This causes the fuzzy control system to waste more acid and base when trying to control the solution. The set point of 9 is a very extreme case. The sulfuric acid equivalence point is about 9.7, which causes the change in pH to be very rapid at this point. The relevant range for hydroponic farming is in reality around a pH of 5.5-6 as that is what most plants prefer [27]. A setpoint of 9 was included to stress test the control systems.

5.3 Overshoot in EC control

For EC control both Fuzzy Logic and PID overshot the target value. Fuzzy Logic by 0.06 and PID by 0.14. The reason for this is probably caused by the system taking some time to circulate the nutrients to the entire water tank. The value continues to rise slowly over about 2 minutes after the target value is reached and the pumps have stopped. This could be resolved by a less aggressive tuning of the control systems. Another answer for this could be time, if the system would be allowed to be on for a longer period than 10 minutes this value could stabilize. If the overshoot is large enough to warrant correction the only way to do it is to add water to the tank or let the plants absorb the nutrients over time but that is not needed in this case.

5.4 Simulation pH

Overall, the pH simulation performs well, but requires some calibration. Because of this, the recommended approach to control and tune a pH-process would first include a test run where the simulation is compared to reality and then tweaked. After this is done. The simulation should be quite reliable and can be used to create an initial setup for the control system. The benefits of this is an accurate system that can be tuned without having the system available. At the start of the simulation when the total concentrations in the solution is close to 0, the behavior is very irregular with rapid changes but this stabilizes after a while. Because of this, the simulation needs some time to stabilize before it acts as an as accurate as possible representation of reality.

5.5 Simulation EC

Simulating EC works well and can be used as a tool for creating a control system. A linear representation is enough, and the only thing that needs to be measured and calibrated is the time it takes for the water to mix with the nutrients. In this case, it was about 8 seconds with good circulation.

5.6 Rate of change in pH based on added acid and base

Figure 4.18 shows the change in base or acid needed to reach a specific target value based on the previous amount of acid and base added. The plot shows that more acid and base is needed to reach the target value if more acid and base has been added previously. The reason for this could be that the added acid has two more equivalence points where the hydrogen ions would discharge, as this is not allowed to happen a reaction could occur that is outside of the scope which essentially buffers the solution. That is to say because only parts of the pH-reaction happens it can be seen as a weak acid being mixed with it's conjugate base. This would results in a buffered solution that is more resistant to change. It would be interesting to see the effects of this when the system has been running for a long time.

5.7 Motor Calibration

The process of calibrating the motors was needed for the PWM control to function properly. Another option would be to get a motor driver or control the transistor with an analog output. The reason this was not used was due to complexity in the code for using the Arduino to control a transistor, as the commands would have to be sent from the Raspberry Pi and go through the Arduino. A motor controller was not used due to cost.

5.8 PID tuning with Zeigler Nichols

The method chosen for tuning the control system worked well for creating an initial PID setup. However, it needed to be fine tuning both in simulation and in the real-life experiment. Having a starting point helped greatly. This method proved to be a bit aggressive and caused some overshoot even with the careful scaling used in this report.

5.9 Equipment

Most equipment worked well but some changes should be made if the project was started today.

5.9.1 Sensors

The EC meter should be changed to an industrial Total Dissolved Solids meter, such as the ECTDS10 made by Seeed Studio [28]. This would be more durable and it can be submerged for a longer time. TDS can easily be converted to EC as they measure the same thing using different units. The only reason this sensor was not picked was that we did not have knowledge of it at the start of the project. All other sensors work as expected, but most pH probes only work for about 6 months of continuous use. This would be fine for a large-scale operation, but for smaller-scale projects a more durable alternative would be better, if it exists.

5.9.2 Micro-controllers

The next version could use an Arduino for both control and sensor measurement. Doing so would enable more accurate control of the motors through the analog output pins as well as simplify the code. The Raspberry Pi would remain but only be used for post processing and network connectivity.

6

Conclusion

For a hydroponic growing system, the environment needs to be controlled, especially the pH and EC values. Creating a control system for pH is a challenge, especially when a triprotic acid is used, which creates a nonlinearities that are hard to handle.

Multiple tests and simulations were performed to create a model of the behavior of pH and EC. These models were then used to create and tune a fuzzy logic and PID controller. These controllers were then tested and fine tuned to control the pH and nutrient levels more accurately.

To use the control systems on a Raspberry Pi with GPIO pins, it was necessary to implement and tune PWM control for the pumps. The PID controller outperforms the fuzzy logic controller when used for pH control, in both speed and stability. For EC the PID controller was faster but less exact when compared to fuzzy logic control. The tuning for both could be improved for better results.

Both a fuzzy control system and a PID control system would work depending on tuning. The tuning along with the capabilities of the pumps is the determining factor of how large or small the system can be. For a small system of about 20 liters the system developed in this report works well and could also be used for larger systems. The changes in pH and EC would be slower in this case.

Bibliography

[1] O. N. Samijayani, R. Darwis, S. Rahmatia, A. Mujadin, and D. Astharini, "Hybrid zigbee and wifi wireless sensor networks for hydroponic monitoring," in *2020 International Conference on Electrical, Communication, and Computer Engineering (ICECCE)*, 2020, pp. 1–4. DOI: `10.1109/ICECCE49384.2020.9179342`.

[2] E. W. Stein, "The Transformative Environmental Effects Large-Scale Indoor Farming May Have On Air, Water, and Soil," *Air, Soil and Water Research*, vol. 14, 1–8, 2021. DOI: `https://doi.org/10.1177/1178622121995819`.

[3] G. Marques, D. Aleixo, and R. Pitarma, "Enhanced hydroponic agriculture environmental monitoring: An internet of things approach," in *Computational Science – ICCS 2019*, J. M. F. Rodrigues, P. J. S. Cardoso, J. Monteiro, R. Lam, V. V. Krzhizhanovskaya, M. H. Lees, J. J. Dongarra, and P. M. Sloot, Eds., Cham: Springer International Publishing, 2019, pp. 658–669, ISBN: 978-3-030-22744-9.

[4] M. van Iersel. (). "Ec and ph: What is it and why does it matter?" [Online]. Available: `https://hortphys.uga.edu/hortphys/files/2020/03/EC-and-pH.pdf`. (accessed: 08.02.2022).

[5] Nidogrow. (2022). "Nido one," [Online]. Available: `https://www.nidopro.com/en/`. (accessed: 26.01.2022).

[6] *Basics of ph control*, ADS 43-001, Rev.C, Emerson, Mar. 2011, (accessed: 14.02.2022).

[7] Marcin Borkowski. (2022). "Phosphoric acid acid titration," [Online]. Available: `http://www.titrations.info/acid-base-titration-phosphoric-acid`. (accessed: 14.02.2022).

[8] LibreTexts, *Titrations and pH Curves.* Open Education Resource (OER), 2020, Online.

[9] J.-P. Ylén, "Measuring, modelling and controlling the pH value and the dynamic chemical state," English, Ph.D. dissertation, Helsinki University of Technology, Control Engineering, 2001, 145, [1], ISBN: 951-22-5783-1. [Online]. Available: `http://urn.fi/urn:nbn:fi:tkk-003251`.

[10] R. F. Newton and M. G. Bolinger, "The dissociation constant of water from an equilibrium involving mercuric oxide and mercurous bromide1," *Journal of the American Chemical Society*, vol. 52, no. 3, 921–925, 1929. DOI: `10.1021/ja01366a012`.

[11] H. Kalka, "Polyprotic acids and beyond—an algebraic approach," *Chemistry*, vol. 3, no. 2, pp. 454–508, 2021, ISSN: 2624-8549. DOI: `10.3390/chemistry3020034`. [Online]. Available: `https://www.mdpi.com/2624-8549/3/2/34`.

[12] Plantprovider, *How to measure and control ec in hydroponics.* [Online]. Available: `https://plantprovider.com/how-to-measure-and-control-ec-in-hydroponics/`, (accessed: 14.02.2022).

[13] P. R. Z. Snehal D.Kambale Sebastian George, “Controllers used in ph neutralization process: A review,” *International Research Journal of Engineering and Technology (IRJET)*, vol. 02, no. 03, 2015, ISSN: 2395-0056. [Online]. Available: `https://www.irjet.net/archives/V2/i3/Irjet-v2i365.pdf`.

[14] K. J. Astrom and L. Rundqwist, “Integrator windup and how to avoid it,” in *1989 American Control Conference*, 1989, pp. 1693–1698. DOI: `10.23919/ACC.1989.4790464`.

[15] M. Labs, *Ziegler-nichols tuning rules for pid.* [Online]. Available: `https://www.mstarlabs.com/control/znrule.html#Ref4`, (accessed: 09.08.2022).

[16] Hardeep Singh, Bruce Dunn. (2016). “Electrical conductivity and ph guide for hydroponics,” [Online]. Available: `https://extension.okstate.edu/fact-sheets/electrical-conductivity-and-ph-guide-for-hydroponics.html`. accessed: 30.11.2022.

[17] Atlas Scientific. (2021). “How does a ph probe work?” [Online]. Available: `https://atlas-scientific.com/blog/how-does-a-ph-probe-work/`. (accessed: 18.09.2022).

[18] ——, (2021). “How do conductivity meters work?” [Online]. Available: `https://atlas-scientific.com/blog/how-do-conductivity-meters-work/`. (accessed: 19.09.2022).

[19] *Diode-based temperature measurement*, SBOA277A, 2, Texas Instruments, May 2019, (accessed: 09.02.2022).

[20] H. Farahani, R. Wagiran, and M. N. Hamidon, “Humidity sensors principle, mechanism, and fabrication technologies: A comprehensive review,” *Sensors*, vol. 14, no. 5, pp. 7881–7939, 2014, (accessed: 09.02.2022).

[21] Rotronic, *The capacitive humidity sensor – how it works attributes of the uncertainty budget.* [Online]. Available: `https://www.rotronic.com/en/humidity_measurement-feuchtemessung-mesure_de_l_humidite/capacitive-sensors-technical-notes-mr`, (accessed: 09.02.2022).

[22] J. A. L. Lee and I. B. Culaba, “Fabrication of a capacitive relative humidity sensor using aluminum thin films deposited on etched printed circuit board,” in *MATEC Web of Conferences*, EDP Sciences, vol. 59, 2016, p. 01 011. [Online]. Available: `https://doi.org/10.1051/matecconf/20165901011`.

[23] United Nations, *Sustainable development goals.* [Online]. Available: `https://www.un.org/sustainabledevelopment/sustainable-development-goals/`, (accessed: 03.02.2022).

[24] ——, (2019). “Ensuring the ‘lungs of the planet’ keep us alive: 5 things you need to know about forests and the un,” [Online]. Available: `https://news.un.org/en/story/2019/05/1038291`. (accessed: 03.02.2022).

[25] World Wildlife Fund, “Indoor soilless farming,” World Wildlife Fund, Tech. Rep., 2020. [Online]. Available: `https://files.worldwildlife.org/wwfcmsprod/files/Publication/file/84omrzpdge_WWW_SoilessAg_Phase1_Final_Report_Full_051320.pdf?_ga=2.123592843.1008277239.1662218337-1045856840.1662218337`, (accessed: 08.09.2022).

[26] E.B. Makartsev, “Hydroponics in extreme conditions.,” XI International Scientific and Practical Conference, p. 171. [Online]. Available: `https://asu.edu.ru/images/File/SBORNIK-YaiMK-XI-noyabr-2018.pdf#page=171`, (accessed: 08.09.2022).

[27] (2017). “Raspberry pi 3 model b,” [Online]. Available: `https://www.raspberrypi.com/products/raspberry-pi-3-model-b/`. accessed: 18.03.2023.

[28] Elfa, *Tds-sensor*. [Online]. Available: `https://tinyurl.com/bdhj23fv`, (accessed: 03.09.2022).

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