EE 316 - Electronic Design Project

Project: P1

Water Level Controller

Final Project Report

11 Jun 2021

Objective

Controlling water level can be very useful at many areas. A system that handles or controls amount of water in tanks, pools or pumps, helps us to save power, money and water, efficiently. Also, continuously and automatically working mechanism is a big advantage in usage areas which needs water twenty-four hours a day. Contrary to what seems, this system uses very different parts to control the tank. So, to make this system efficient and sensitive like we want, we also need to know how every part works in itself. Hence, we want to build a system that we can choose a water level, electrodes detect that, and our self-protective circuit system run the pump motor. This system needs to be sensitive and can work in a continuous operation.

Group Members

Common efforts: Oscillator circuits and motor driver.

Barbaros İnak: Electrode system and detection circuit.

Ahmet Yasin Bulut: PWM generation and driver circuits.

Emre Nedim Hepsağ: Error amplifier, DC motor pump and protection control.

Revision History

Week-5: Four possible detection circuits for low pass filtering are designed. We decided that the simplest circuit is better, and the other versions are not enough stable for settling time and ripple to concede from simplicity.

Week-7: The xor values on the simulation are changed to generate a 5V output. This change discarded the amplifier need at the output, and add more simplicity to the circuit.

Week-8: The buffers are added at the differential output inputs to decrease distortions, so the connections can't apply loading effect.

Week-9: The triangle generator design completely determined; the feedback resistor value need to be calculated.

Week-11: We decided to change operating voltage range from 0-5V to 1-4V, this change helps to avoid working at limits, so the overvoltage errors, but decrease the accuracy because of the lower voltage gap. Also, the maximum difference of two signals are decreased to 3V, the PWM inverting opamp will be redesigned.

Week-12: The source voltage values are gathered together, then all resistance values are standardized and the design revised.

1. Introduction

We need to solve these three design problems to control the water level:

a. Detection of water level: To control the motor pump, the water level is supposed to be detected. Capacitance of the cylindrical capacitor inside the water tank changes due to the water level. Change in capacitance gives greater delay to the pulse oscillation which is generated from 555 IC and connected to capacitor. The delay at the pulse waves are being turned into DC signal thanks to xor gates as digitalizer and simple RC lowpass filter.

b. Adjusting desired level: The signal coming from RC filter is supposed to be amplified to mV to V range. Because the maximum and the minimum voltage values which are coming from potentiometer are from 1 to 4 volts. To give potentiometer the power of controlling the water level is coming from the differentiating the amplified signal from potentiometer voltage which is done with differential amplifier.

c. Controlling motor: To feed l298, we needed an PWM signal. Thus, we built another 555 circuit to generate 25kHz pulse signal and integrated it with opamp to make it triangular wave. Then we adjusted its level with inverting amplifier. In order to generate PWM output, both error amplifier and triangular wave signals are connected to comparator to generate PWM signal. And finally, the PWM output is connected to l298 IC to control the DC motor. In addition, to protect the DC motor, overcurrent protection circuit is added to the circuit.

The different water level detection designs are examined in similar projects, but the capacitive water tank is seeming easier to use, in the way of connecting an RC circuit and putting an oscillator in detecting.

Alternative to 555 IC, it is possible to use different kind of oscillation circuits. Such as; Wien bridge oscillator and crystal oscillator. These circuits also designed and their effectiveness is observed for this project. We ended up choosing 555 oscillator because of the simplicity and give up the better stability of other oscillator circuits.

1.1 Electrode System & Detection Circuit
1.1.1 Electrode System

When two parallel plates have been charged, an electric field created between those plates. This electric field happened due to the charged structure of conductive plates. Therefore, these plates act like capacitors. When a dielectric material has put between a capacitor’s plates, capacitance will rise. This concept has been used for determining water level. Water between plates have been treated as dielectric material. For this experiment different kind of structures of plates have been checked. For example, cylindrical rods, cylindrical tubes, and multiplate capacitors. Among given examples we decided to use cylindrical tubes due to the better noise performance and easy producibility.

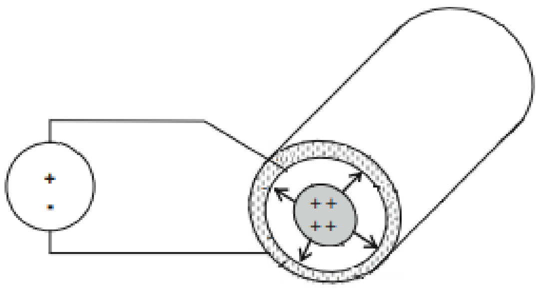


Figure 1. Sample schematic for chosen capacitor style [1]

1.1.2 Detection Circuit

Detection circuit tries to detect the water level according to the delay, that happened because of the capacitor. First, the delayed signal should be digitalized with using xor gate as buffer. Coming signal should be digitalized for better analysis, since the input is square wave. Xor gate have been used here for saving area and component. Because in the further operations for getting the delayed part another xor gate will be needed. After maintaining digitalized delayed signal, delay signal could be found by using a xor gate with inputs as input square wave and digitalized delay signal could be obtained.

1.2. PWM Generation & Driver Circuits
1.2.1 Switching power supplies

Basic linear drivers are easy to design but the power dissipation is not effective, the circuit is always working and has no time to cooling down. The constant bias also complicates the calculation and make difficult to obtain the exact voltage level. On the other side, switching mode power supplies is very efficient, and has low power dissipation.

1.2.2 Pulse width modulation

In this modulation, speed control works by driving the motor on and off, its fraction is called duty ratio. Duty ratio helps us the adjust average voltage and average power levels. Rotational speed of the DC motor is directly related to the average voltage value, so longer “on” means greater duty ratio means faster motor. Using Pulse Width Modulation (PWM) in drivers are important because of the inductive nature of the DC motors. The magnetic energy in inductive load needs to be dissipated. Inductive load’s stored magnetic energy can become a negative voltage to maintain the same current level when the circuit is switched off. This effect can damage the circuit and we need to dissipate this stored energy safely.[2] In PWM we always drive the motor at full strength, this effect helps demagnetization. Also, its switching operation helps circuit to cooling down, so make it more efficient and safer. Moreover, DC motors' high current demand can burn regulators and even ICs connected to drive them. So, selecting a special motor driver circuit is essential to give them high voltage and also high current values.

The motor direction control also can be needed, and it can be done with different switches which changes motor terminals. A mostly used configuration of switches is called H configuration, can do forward, reverse and stopping operations. The more complex bridge configurations can be used in different circuits.

1.3. DC Motor Pump & Protection Control

1.3.1 DC Motor and Torque Generation

DC motor represents a type of rotary electrical motors. They consist of rotor (armature), stator, commutator, and brush. Simply, coil of rotor draws DC current and creates magnetic field which interacts with permanent magnet thanks to Lorentz Force and that generates torque. While the motor is rotating, because of commutator and brush, the direction of the current does change and creates continuous rotation. Consequently, we can say that DC motor is a rotating machine which is converting electric energy into torque by electromagnetism.

$$\text{Torque of Rotator} = \mathrm{T_r} = \frac{PZ}{2\pi A} \times \Phi \mathrm{I_a}$$

P: *Number of field poles*, Z: *Total numer of rotator conductor*, Φ: Flux produced per pole,

$\mathrm{I_a}$: Current that rotator draws, A: Number of parallel paths in rotator, N: Rotational speed

1.3.2 DC Motor Characteristics

There are different kinds of DC motors which are permanent magnet DC motors, series DC motors, shunt DC motors and compound DC motors. According to these kinds, as we can see at Figure 2 we observe different characteristics among speed, torque, and armature current. Here are the characteristic curves of Torque/Current, Speed/Current and Speed/Torque. For our application, we need a motor whose speed is able to be controlled. Because of that, series motor is our selection. In that kind of motor, high torque is needed to start the motor. As in seen, without mechanical load/torque, the speed goes dramatically high. Lastly, there is inverse relation between speed and torque [3].

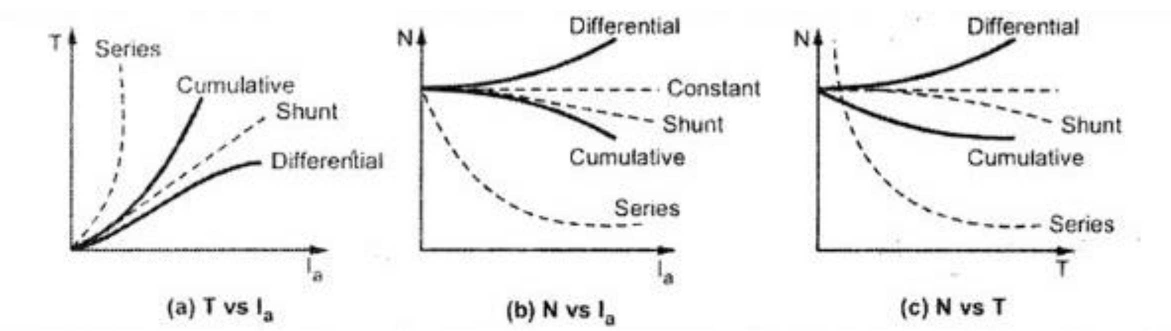


Figure 2: Characteristics of DC Motors [4]

1.3.3 Back EMF Generation

In DC motors, we observe an opposing current from the motor which is because of back electromotive force. Back EMF occurs because while the motor is working, the coils of the rotator cut the magnetic flux constantly and that creates back EMF induces on the rotator due to Faraday's Law of electromagnetic induction. The direction of this induction is opposing to the current that goes into rotator.

There is directly proportional relation between rotational speed and the magnitude of the back EMF. If the load on the dc motor drops, torque drops, that results in increment on the speed. Rise on speed makes the magnitude of the back EMF rise. Because of that, current declines. If the opposite takes place, we observe current to be increased. Due to back EMF, those relevant steps make motor to be self-regulated.

$$Back\ EMF\ for\ DC\ motor = E_b = \frac{\Phi \mathrm{ZN}}{60} \mathrm{x} \frac{\mathrm{P}}{A}$$

Φ : Flux produced per pole, Z: $Total\ numer\ of\ rotator\ conductor$, N: Rotational speed,
P: $Number\ of\ field\ poles$, A: Number of parallel paths in rotator

1.3.4 Closed Loop Proportional Control

Closed loop proportional system means that there is a closed loop system whose output is proportional to the error signal. Thus, it tries to keep the variable value at desired level with least deviation. Simply, there is a parameter which is supposed to be controlled. Thanks to negative feedback which is coming from closed loop, the system controls the output value proportional to the error signal. As a result, we obtain an automated PID systems which controls the output at adjusted value.

Proportional Integral Derivative (PID) control systems are widely used in industry and it is accepted all around the world. They have been used for years and they have many application areas. There are different types of PID control methods which are proportional, On/Off and standard [5]. However, we are going to use proportional controller circuit. Typically, there are three responses on PID control algorithm: proportional, integral, and derivative. They are added or subtracted for different purposes. Ideally, the system has 3 of the responses. However, in our circuit proportional response is adequate.

1.3.5 Overcurrent Protection

Overcurrent protection control is a crucial feature of a circuit. It limits the system to draw greater current than it is supposed to. We do not want any component to be broken at edge situations. Especially DC motors, they are easy to be broken at high current.

An overcurrent protection circuit can be built by a current sense resistor and a comparator with a reference voltage. Current sense resistors are small valued, high precision resistors which are being used for measuring the current. They are small valued because it is not wanted them to consume power of the circuit. Also, low power consumption results in less heating up which makes them more accurate and less dependent to the heating for measuring purposes [6].

2. Technical Description

The water level of the tank is obtained with a capacitive cylinder placed in the water tank. The cylinder is connected to detection circuit, and its value gives us the current water level. An error amplifier finds how much water we need for desired level, this desired level is adjusting with potentiometer. PWM generation circuit produce signals with different duty cycles depending of water needed. Motor driver uses PWM directly to pump the water with DC motor, protection circuit blocks the over current to protect to motor.

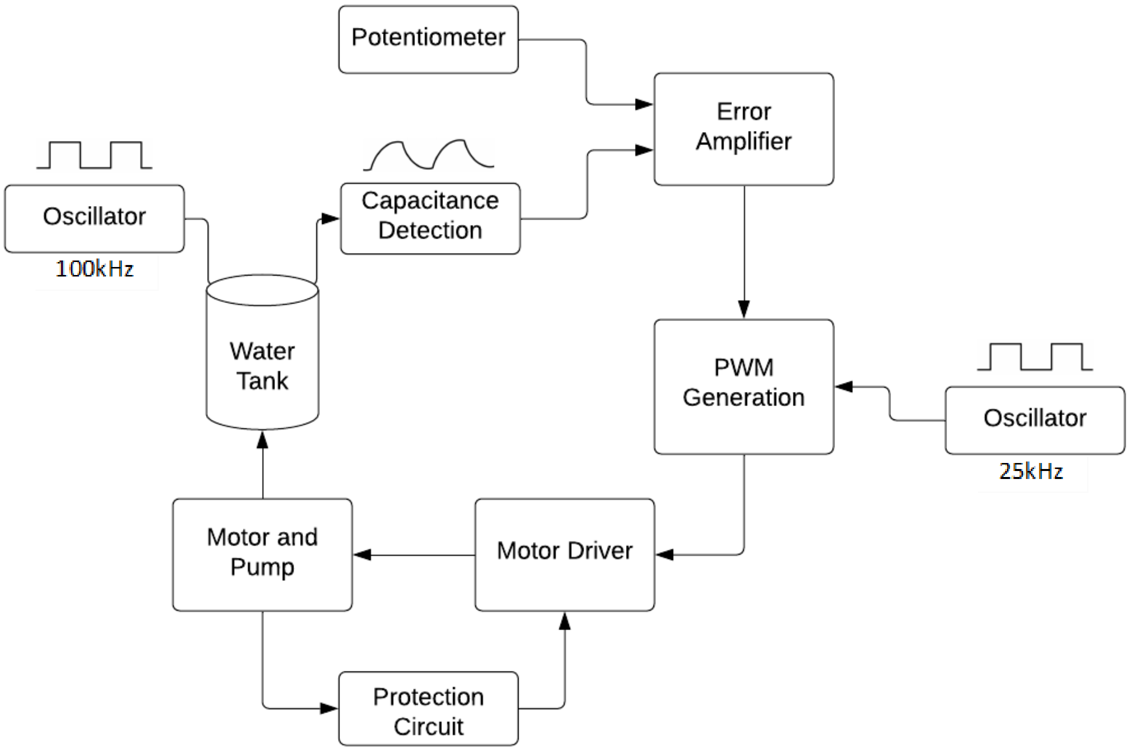


Figure 3. Block diagram of the water level controller.

The different ways of PWM generation methods and motor control methods are examined and designed for prototyping. We choose the simple methods for realizing this project, the different generation methods can also work, and may want to be selected to design a more stable and accurate project.

2.1. Water Level Detection

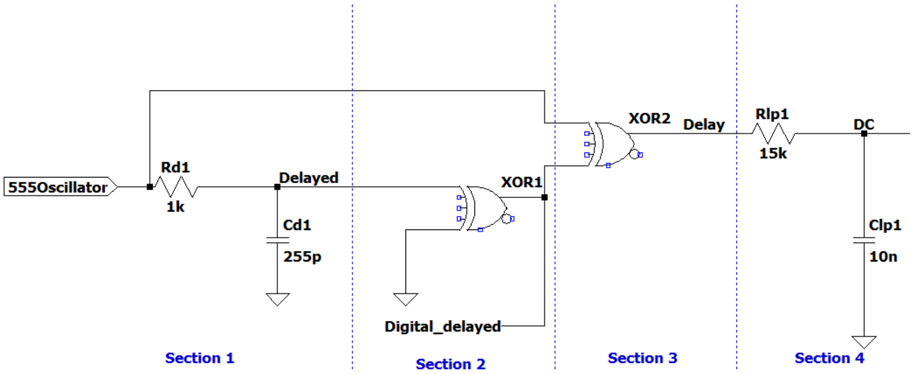


Figure 4. Water level detection circuit.

Delayed Circuit

Delayed circuit is located in the section 1 in Figure 4. For finding the delay happened due to the capacitive effect of the water level, a simple RC circuit have been used. Resistor and capacitor have been connected in series. Resistance value have been chosen as 1 kΩ. Resistance value have been chosen according to real resistance values and time constant (τ) of the RC circuit.

$$\tau = R_{d1} \cdot C_{d1} = 0.255\ ns$$

τ is shorter than oscillator's period. Since oscillator's period is around $10\ \mu s$. In section 1, capacitor represents the cylindrical capacitor's instantaneous value. Also, capacitor have been chosen as cylindrical.

$$C_{d1} = \frac{\pi\ \epsilon_0\ \epsilon_r}{\ln \frac{r_b}{r_a}} \cdot x + \frac{\pi\ \epsilon_0}{\ln \frac{r_b}{r_a}}\ (L - x)\ F$$

$\epsilon_0$shows the dielectric constant of air, $\epsilon_r$represents the dielectric constant of water, according to "Relative permittivity" (2021) water's dielectric constant is equal to 80.2 [7] when the room's temperature is at 20°C. r_b and r_a corresponds to the radius values of outer cylinder and inner cylinder, respectively. x is water's level in the capacitor and L is the total length of the capacitor.

Digitalizer

Digitalizer circuit has been shown in the Figure 4's second section. Digitalizer circuit makes the delay signal has sharp edges instead of curvy edges. By giving inputs of the xor as delay signal and 0 we get a buffer behavior. At the output we get delayed version of oscillator's output.

Delay Signal Generation

Section 3 in the Figure 4, shows the delayed signal generation circuit. Error signal shows the different parts of oscillator's output and digitalized delayed signal. For obtaining this condition a xor gate could be used. At the output we see ones at delay points.

Low Pass Filter

Low pass filter is in section 4, which has been shown in Figure 4. For finding the DC part of the delayed signal, we used a low pass filter configuration with a resistance and a capacitor. We have chosen resistance and capacitance values as universality and cost. Corner frequency of shown circuit as follows,

$$f_C = \frac{1}{2\pi\, R_{lp1}\, C_{lp1}} = \frac{1}{2\pi\ 15x10^3\ \Omega\ \ 10x10^{-9}\ F} = 1.061\ kHz$$

As a result of given circuit, we ended up with a DC like signal with ripple. We tried to have a ripple around 3%. The filter that we have used is sufficient enough to have a ripple percent around intended value. An example calculation as follows,

$$Ripple\ percent = \frac{4.95\ mV}{158.41\ mV} \cdot 100\% = 3.12\ \%$$

By completing these steps, we finally obtained voltage value in accordance with water level in the tank.

Water Level Detection Design Targets			
Description of Design Targets	**Min.**	**Max.**	**Units**
Oscillator Frequency	**98**	**102**	**kHz**
Detector Response Time	**125**	**225**	**ns**
Detector output at 5 cm water level	**90**	**100**	**mV**
Detector output at 15 cm water level	**180**	**190**	**mV**
Ripple Voltage	**2.7**	**5.7**	**mV**

Table 1. Design targets of water level detection circuit.

2.2. Error Amplifier

Noninverting amplifier circuit does Amplification and offset addition. After amplifying the DC signal from mV to V level, error amplifier substitutes it from the signal coming from potentiometer.

Noninverting Amplifier

Values of DC signal are minimum 94mV and maximum 182mV. However, the voltage on the potentiometer is from 1 to 4 volts. We aimed 1-volt gaps at max and min to minimize real life errors, also to obtain reasonable values. Thus, noninverting amplifier circuit at Figure 5 changes the range of DC from 1.09V to 4.10V.

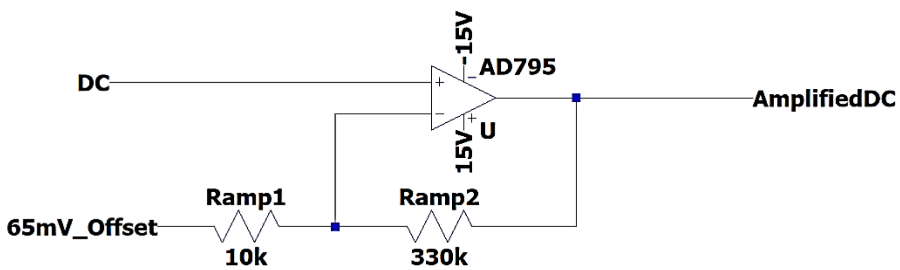


Figure 5. Circuit diagram of noninverting amplifier circuit.

The gap between maximum and minimum voltages increased to approximately 3 volts. Thus, voltage gain is obtained as 34.

$$\Delta V = 182m - 94m = 88mV, \quad \Delta V * 34 = 2.992 \approx 3V$$

$$A_{v1} = \frac{R_f}{R_i} + 1 = \frac{330k}{10k} + 1 = 34\ (Gain\ of\ Noninverting\ Amplifier)$$

The offset is added to make the signal start from approximately 1 volt.

$$A_{v2} = -\frac{R_f}{R_i} = -\frac{330k}{10k} = -33\ (Gain\ of\ Inverting\ Amplifier\ for\ offset),$$

$$94m * 34 + V_{offset\ Output} \approx 1V$$

$$V_{offset\ Output} = 65m * (-33) = -2.145V$$

$$v_{AmplifiedDC\ Min} = 94m * 34 - 2.145 = 1.051V$$

$$v_{AmplifiedDC\ Max} = 182m * 34 - 2.145 = 4.043V$$

Differential Amplifier

Our aim is to subtract AmplifiedDC from the PotOut which is the voltage on potentiometer. Thus, we designed a typical differential amplifier opamp circuit at Figure 6 which has identical resistor.

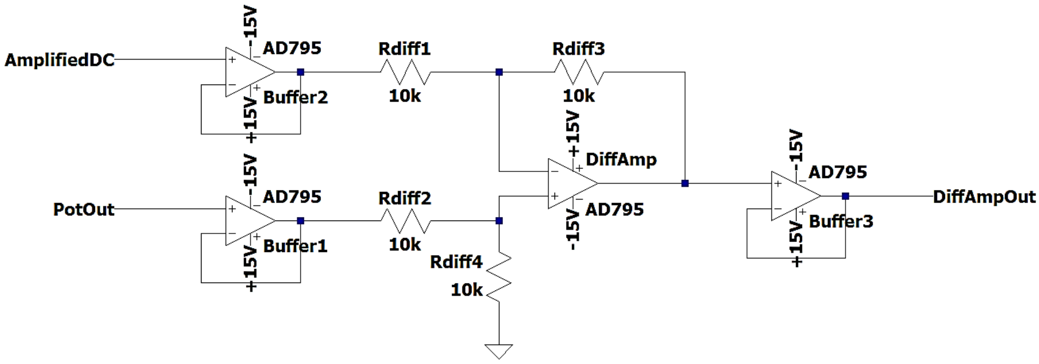


Figure 6. Circuit diagram of error amplifier circuit.

$$\text{Differential Op Amp Formula} => \quad V_{Out} = \left(\frac{R_4}{R_3+R_4}\right) * \left(\frac{R_1+R_2}{R_1}\right) * V_2 - \frac{R_2}{R_1} * V_1$$

However, our all resistors are the same value. Thus, it turns into:

$$V_{DiffAmpOut} = V_{PotOut} - V_{AmplifiedDc}$$

$$V_{DiffAmpOut\ Min} = V_{PotOut}(Min) - V_{AmplifiedDc}(Max) = 1.051 - 4 = -2.949$$

$$V_{DiffAmpOut\ Max} = V_{PotOut}(Max) - V_{AmplifiedDc}(Min) = 4.043 - 1 = 3.043$$

We want the user to change the potentiometer from 1 to 4 volts. Because it is not possible to be accurate with potentiometer in real life. Due to these situations, over 3V designed as maximum, under 0V is designed as minimum for PWM generation.

Error Amplifier Design Targets			
Description of design target	**Min.**	**Max.**	**Unit**
Noninverting Amplifier Output Low voltage	**1**	**1.1**	**V**
Noninverting Amplifier Output High voltage	**3.8**	**4.2**	**V**
Noninverting Amplifier Gain	**33**	**35**	**-**
Potentiometer Output	**0.5**	**4.5**	**V**
Output Low Voltage	**-2.8**	**-3.1**	**V**
Output High Voltage	**2.9**	**3.2**	**V**

Table 2. Design targets for the error amplifier.

2.3. PWM Generation

The designed water level controller motor, needs high current to drive and needs to be efficient while it can cool down, pulse width modulation is the best choice for these purposes. The circuit use DC input that gives us the information of the water amount we want and an oscillator input to generate a square wave signal with different duty cycles for use at the motor driver directly. Circuit has a triangle generator and an inverting amplifier to generate a comparable signal with the DC information. Then with a comparator, PWM signal is generated.

Triangle Generator

The simple integrator circuit shown in Figure 7 generates the triangle signal from a clock signal. The feedback capacitor makes output voltage proportional to the time integral of V_{osc}. Because of input offset at the lm555 oscillator, which is $V_{on}/2 = 2.5V$, the integrator saturates the opamp near negative supply voltage, so a feedback resistor is added to avoid this problem.

$$V_{osc} = R_i i_i = R_i * (i_c + i_R)$$
$$V_o = -V_c$$
$$i_R = \frac{V_o}{R_f}$$
$$V_o = \frac{1}{C_f}\int i_c\, dt \text{ and } i_c = \frac{V_{osc} - R_i i_R}{R_i}$$
$$-V_o = \frac{1}{C_f R_i}\int V_{osc} dt + \frac{1}{C_f R_f}\int V_o dt$$

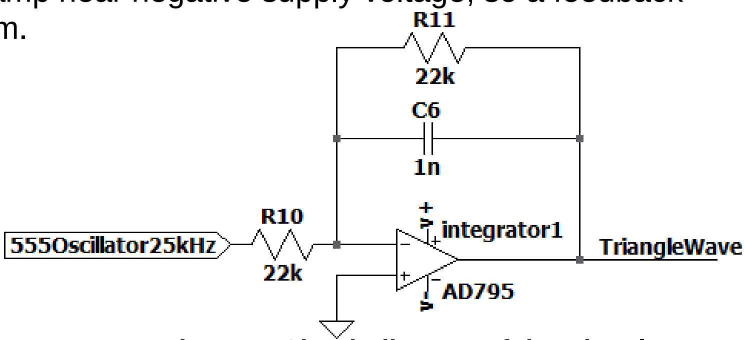


Figure 7. Circuit diagram of the triangle generator.

First part of this equation determines the gain and the time constant. We need a big time constant to generate a nearly linear triangle edge. Second part is giving us dc offset, determines the offset gain and for better accuracy feedback time constant Rf*Cf also needs to be greater than the period.

We know the capacitance charging and discharging equations are

$$V_{charge} = V\left(1 - e^{-\frac{t}{RC}}\right) \text{ and } V_{discharge} = V\left(e^{-\frac{t}{RC}}\right)$$

For symmetric triangle, find common solution of them

$$\left(1 - e^{-\frac{t}{RC}}\right) = \left(e^{-\frac{t}{RC}}\right) \rightarrow\ 1 = 2\left(e^{-\frac{t}{RC}}\right) \rightarrow 0.693 = \frac{RC}{t} \rightarrow RC = 0.693 * T$$

We used 25kHz pulse wave for matching the frequency with l298 motor driver, so the RC value equal to 27.72u. We should choose Ri big enough to oscillator drive it easily (>1k). For these purposes, 22kOhm resistance and 1nF capacitor are selected. Rf value directly selected same as Ri, and the output offset is $R_i/R_f * offset = 2.5V$. Because of charging and discharging time intervals are the same, the capacitor can only be %50 charged, so the peak-to-peak amplitude of the triangle is $5V * \%50 = 2.5V$. Finally, don’t forget that this operation is inverting, so the peak amplitudes are

$$-V_{offset} \pm \frac{V_{opp}}{2} \rightarrow -2.5 - 1.25 =\ -3.75\, min\, and - 2.5 + 1.25 = -1.25\, max$$

Inverting Opamp & Comparator

The simple inverting opamp circuit shown in Figure 8 is used for converting the integrator output to usable signal at comparator. Then a fast opamp used like a comparator to create a pulse signal with comparing a triangle and a DC wave we generated. For cancelling the integrator output offset, an offset voltage (-5V) is used at the noninverting terminal.

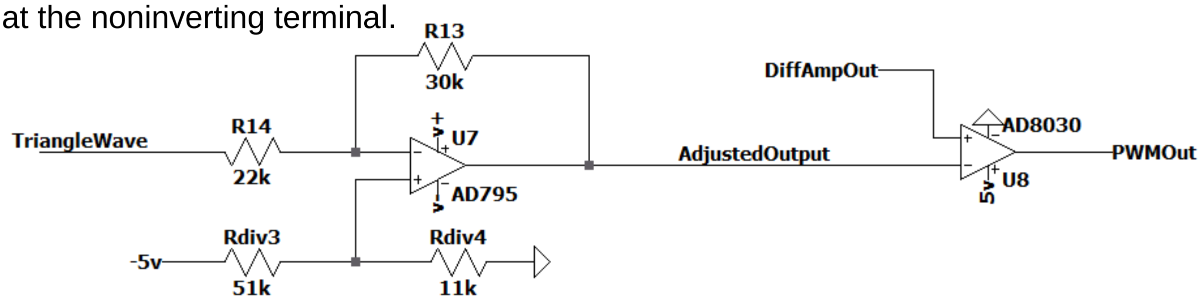


Figure 8. Circuit diagram of the inverting opamp with offset

We need our triangle signal between 0V-3V as same range as the differential amplifier output. The inverting amplifier equation is

$$V_{out} = -\frac{R_f}{R_{in}} V_{in} + \left(1 + \frac{R_f}{R_{in}}\right) V_{offset}$$

$$At\ peaks;\ 3 = -\frac{R_f}{R_{in}} * -3.75 + \left(1 + \frac{R_f}{R_{in}}\right) V_{offset}\ (I)$$

$$0 = -\frac{R_f}{R_{in}} * -1.25 + \left(1 + \frac{R_f}{R_{in}}\right) V_{offset}\ (II)$$

$$(I) - (II) = 3 - 0 = -\frac{R_f}{R_{in}} * -(3.75 - 1.25) = \frac{R_f}{R_{in}} * 2.5 \rightarrow \frac{R_f}{R_{in}} = \frac{6}{5} = 1.2$$

Then the DC offset is

$$0 = -\frac{6}{5} * -1.25 + \left(1 + \frac{6}{5}\right) V_{offset} \rightarrow V_{offset} = 0.68\ V$$

With the standard values we select Ri = 22k, Rf = 30k, then we adjust a offset with observing simulation results and considering standard values, 11k and 50k valued voltage divider works for operation.

Comparator works at opamp voltage limits, so we give positive and negative supply voltages as we want at the PWM signal. The comparing is between 25kHz wave and DC wave, so the output frequency is also 25kHz, and it is ideal value for the l298 motor driver. All offset and amplitude values are adjusted for this operation, so we don't need any other component to generate the PWM signal.

PWM Generator Design Targets			
Description of Design Targets	**Min.**	**Max.**	**Units**
PWM frequency	**24.5**	**25.5**	**kHz**
Integrator time constant	**25.5**	**29.8**	**s**
Triangle wave slew rate (increasing & decreasing)	**±0.075**	**±0.125**	**V/us**
Inverting opamp peak-top-peak gain	**0.98**	**1.47**	**-**
Inverting opamp DC offset	**0.50**	**0.92**	**V**
PWM comparator input for %0 duty cycle	**-0.20**	**0.33**	**V**
PWM comparator input for %100 duty cycle	**2.18**	**4.00**	**V**

Table 3. Design targets for the PWM Generator circuit.

2.4. Motor Driver and Protection

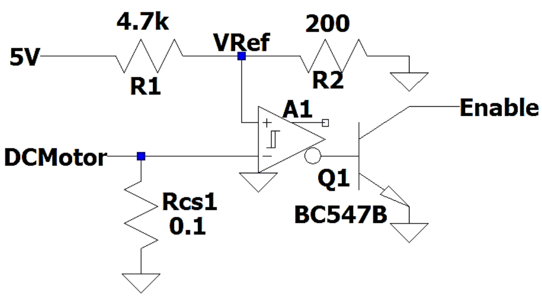
To pump water to the bottle, we need to convert PWM signals into current to drive the DC motor under desired current limit.

Motor driver

Our circuit does voltage based operations within microampere range, however DC motors work with ampere range current. To control the motor with voltage, we need motor driver as an interface of PWM output and DC motor. It is l298 in this project. Essentially there are voltage supply, enable, input and output pins. We connected PWMOut to enable pin of l298. It is used for controlling the motor speed according to PWM and supplied voltages.

Over-current Protection

Overcurrent protection circuit at Figure 9 protects the motor to draw current higher than 2 amperes. Because high current may damage the DC motor easily. Current sense resistor turns current into voltage. Then the comparator works if the DCMotor voltage is greater than VRef. The negative output of the comparator connected to NPN transistor which works as a switch. If comparator works, collector pin of the NPN pulls Enable down to stop the motor driver.



$$VRef = 5V * \frac{200}{4700 + 200} = 0.204V \ \ (I)$$
$$Voltage\ on\ DCMotor = I(Rotor) * 0.1 \ \ (II)$$
$$Enable\ (NPN\ is\ active) = 0V$$
$$Comparator\ Output\ when\ (II) > (I) = 5V$$
$$Comparator\ Output\ when\ (I) > (II) = 0V$$

Figure 9. Circuit diagram of the over-current protection circuit.

Motor Driver and Protection Design Targets			
Description of design target	**Min.**	**Max.**	**Unit**
Maximum output current without protection	**2.3**	**2.5**	**A**
Expected ripple current depending on motor inductance	**0**	**100**	**mA**
Expected average output current at maximum output	**2.03**	**2.05**	**A**
Overcurrent Protection Current Threshold	**2.02**	**2.06**	**A**
Overcurrent Protection Response Time	**5.5**	**7.5**	**us**

Table 4. Design targets for the Motor Driver and Protection circuit.

3. Test Results

3.1. Water Level Detection Test Results

The measurements have done for the water level detection circuit are available in the given table.

Water Level Detection Test Results		
Design Target	**Measured value**	**Unit**
Oscillator Frequency	**101.01**	**kHz**
Detector Response Time	**184.26 - 380**	**ns**
Detector output at 5 cm water level	**94.87 - 98.08**	**mV**
Detector output at 15 cm water level	**181.06 - 187.06**	**mV**
Ripple Voltage	**3.21 - 6.01**	**mV**

Table 5. Test results for the water level detector.

Nearly all of the results are between design targets. There is 56.06 ns difference between minimum detector response time and 155 ns difference between maximum detector response time. This happened because of the unexpected loading effect that takes it source from mainly 555 oscillator. Also, there is 0.5 mV difference between ripple voltage values. Like in oscillator frequency, we have this error due to the loading effect. Following graphs are going to show some of the important signals.

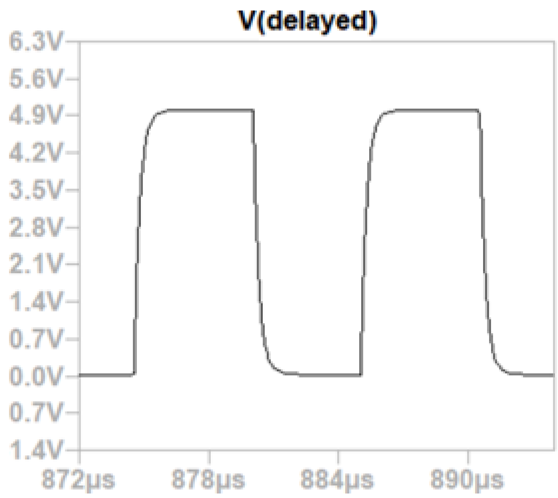


Figure 10. Delayed circuit's output signal.

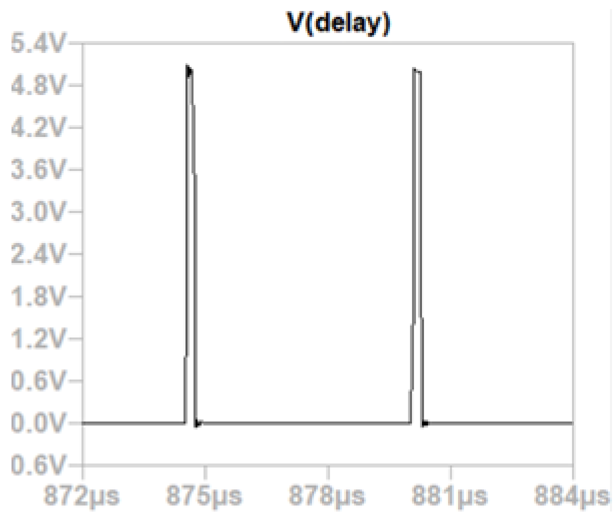


Figure 11. Delay circuit's output signal.

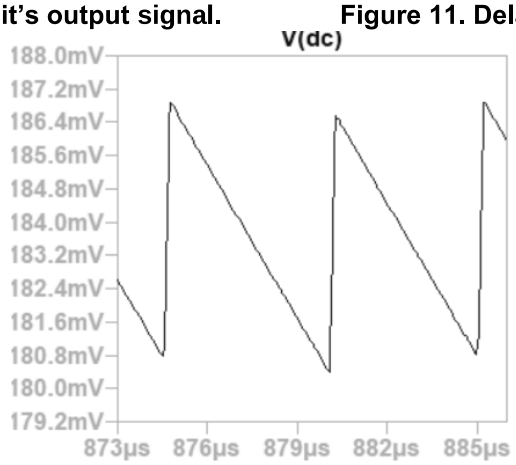


Figure 12. DC signal and Ripple on DC signal.

3.2. Error Amplifier Test Results

The measurements related to the error amplifier circuit design targets are shown in the following table.

Error Amplifier Test Results		
Design Targets	**Measured Value**	**Units**
Noninverting Amplifier Output Low voltage	**1.061 - 1.082**	**V**
Noninverting Amplifier Output High voltage	**4.070 - 4.108**	**V**
Noninverting Amplifier Gain	**33.3 - 34.5**	**-**
Potentiometer Output	**0.5 - 4.5**	**V**
Output Low Voltage	**2.88 - 2.90**	**V**
Output High Voltage	**-3.11 - -3.08**	**V**

Table 6. Test results for the error amplifier circuit.

Noninverting amplifier adds desired DC offset and turns the range of the input signal into desired level properly. Thanks to buffers we used to prevent loading effect; error amplifier subtracts amplified DC from potentiometer output with no flaw. Due to ripple on the input signal, at all nodes we observed unstable values. However, there no dramatic difference to affect our circuit in a bad way. Only the input high voltage is 1mV higher than design target.

3.3. PWM Generation Test Results

The test measurements have done for the PWM generator circuit are given in the table

PWM Generator Test Results		
Design Targets	**Measured Value**	**Units**
PWM frequency	**24.53**	**kHz**
Integrator time constant	**26.52**	**s**
Triangle wave slew rate (increasing & decreasing)	**±0.112**	**V/us**
Inverting opamp peak-top-peak gain	**0.67 - 0.83**	**-**
Inverting opamp DC offset	**0.83**	**V**
PWM comparator input for 0% duty cycle	**0.20 - 0.07**	**V**
PWM comparator input for 100% duty cycle	**2.65 - 3.05**	**V**

Table 7. Test Results for the PWM Generator circuit.

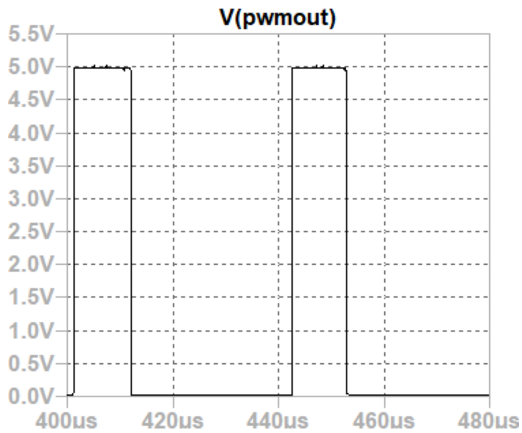


Figure 13. PWM out for 2cm water desire

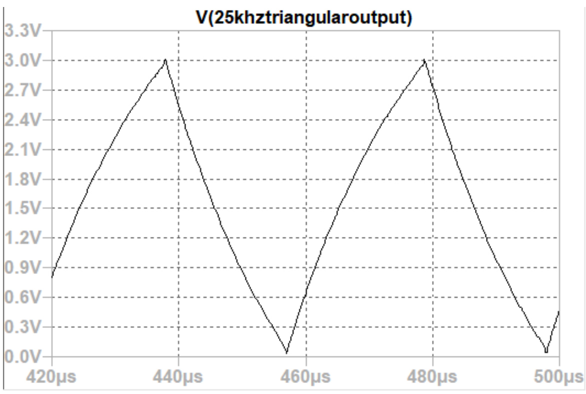


Figure 14. Triangle Output Waveform

The PWM generator generated 24.5kHz PWM signal at Figure 13, and despite the opamp gain difference, the final output works well, and can make 0% and 100% duty cycles as we wish. The time constant and the slew rates of the generated triangle are like we designed (Fig.14), and they don't affect by the other connections. But at the inverting opamp the designed values are decreased ~40%. This is because of the input resistance of the integrator and the effect of the output connections with comparator. This error has no significant effect on generated PWM and be dissipated with integrator and comparator signals. The positive parts which we are considering at generating PWM signal, show no distorted effect and the PWM can be generated accurately despite the distorted bottom triangles. At 13 cm water level and maximum water level desire (15 cm) the PWM output can be seen on Figure 13 has a smooth PWM signal.

3.4. Motor Driver and Protection

The measurements corresponding to the motor driver and protection circuit design targets are representing in the table below.

Motor Driver and Protection Test Results		
Design Targets	**Measured Value**	**Units**
Maximum output current without protection	**2.406 - 2.421**	**A**
Expected ripple current depending on motor inductance	**0 - 92.44mA**	**mA**
Expected average output current at maximum output	**2.038**	**A**
Overcurrent Protection Current Threshold	**2.051**	**A**
Overcurrent Protection Response Time	**6.279**	**us**

Table 8. Test results for the motor driver and protection circuit.

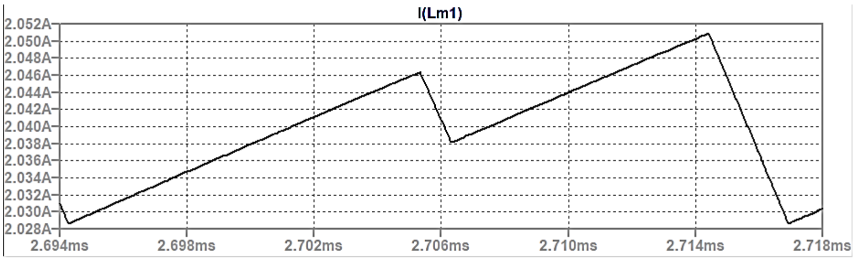


Figure 15. Maximum armature current ripple waveform

The features of the l298 are specified on the datasheet. Thus, it works as expected within the range at design targets. l298 is fed with PWM signal from PWM generation circuit. With that input, the driver turns that input data into output current to drive DC motor. There is additional overcurrent protection circuit connected to the driver. It makes the DC motor works under approximately 2 Amperes as seen at Figure 15. We observe ripple at current because overcurrent protection circuit pulls the enable pin of l298 to the ground to decrease the output current with ripples. It works similar to on-off control system.

4. Conclusion

The water level control system is efficiently designed, the detection system gets the information as capacitive change, the digital conversions and taking the delay size works well. But in physical implementation, there is a little error at the start of digital delayed signal and oscillator difference, which seems a small delay signal occurs at every period, this didn’t affect the system, but if the clock has fluctuant duty cycle the DC voltage will be increased at errors.

Error amplifier subtracting the amplified dc signal from the potentiometer input. It was not directly possible to do substitution because of the range difference. Firstly, we had to amplify the DC voltage from mV range to 0 to 5V range. Due to the starting gap of the DC voltage, it was not possible to do that just with simple opamp. Thus, we added an offset to the circuit with the opamp to solve that problem. Also, the results were not as we expected because of the loading effects, the buffer implementation solved this problem, at physical implementation we did not need such a stabilization.

PWM generator and motor driver designs complete the systems actuator side. Performance of the PWM signal is not perfect because of the continuous operation of pumping, changes the value all the time. We could use PI control for stabilize the PWM and the driver circuit. Design specifications are provided well, except the opamp output voltage range, this change is very huge at the signal side, but it does not affect the PWM generation, if it affects the output, we need to make it more accurate with trying to decrease loading effects. This circuit can be improved with more stable clock circuits, different triangle & PWM generation methods and of course the PI control for continuous process.

DC motors tend to be broken at higher currents than they are supposed to draw. Maximum current limit of our DC motor is 2 Amperes. However, we used directly l298 to control DC motor with PWM signal and it generated higher than 2.4 amperes. Thus, we added over-current protection circuit built with current sense resistor to pull the enable pin of the IC down to the ground when it passes 2 amperes.

5. Component List

Component description	Part Number	Manufacturer
Low Power Low Noise Precision FET Op Amp	**AD795**	Analog Devices
555 Precision Timer	**NE555**	Texas Instruments
Dual High-Speed Operational Amplifier	**AD8030**	Analog Devices
NPN General Purpose Transistor	**BC547B**	Farnell
Single High-Speed Voltage Comparator	**LM311/LM393**	Texas Instruments
Dual Full-Bridge Driver	**L298**	STmicroelectronics

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