EE 316 - Electronic Design Project

Project: P2

DC Motor Speed Controller

Final Project Report
27 May 2019

Objective

This project can be examined in the three parts.

First part is controlling dc motor accurately. The important point is driving the motor with a PWM signal with respect to the duty cycle. Duty cycle is changing according to the error signal. The error signal is determined by taking the difference of obtained voltage from monostable multi-vibrator and adjusted input voltage.

In the second part, according to this error signal oscillator circuit generates pulses which have different duty cycles. To drive the motor, the signal is sent to the half-bridge driver then the motor starts to turn. The speed of the motor depends on the duty cycles. A perforated disc attached to the motor's shaft. A led and phototransistor placed near the disk. While the disk is turning, phototransistor generates the pulse signal. The frequency of this signal depends on the speed of the motor. Then the signal transmitted to the monostable multivibrator.

The aim of the last part is monitoring rpm on the BCD screen. Briefly, duty is driving the motor with a specific duty cycle and generate the error signal to control it's accuracy.

Group Members

Common efforts: Controlling motor with using PWM, Generating Signal and Error Detection, Using 3-Digit 7 Segment Display

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Revision History

Week-5: According to the feedback of the first report, we realized that the misunderstand error detection. Instead of taking the difference of MMV output signal and control signal which we adjusted with a potentiometer, we took the difference of MMV output signal and motor input voltage.

Week-6: When we checked the output signal of the phototransistor, we noticed that the output signal was not the same as expected. It was around 0-5 V so there was no need to transform output signal current to voltage. That's why we discard the LM358 IC.

Week-11: The design of the display part was changed. Because the aim of the first design was monitoring the rpm after according to the professor's suggestion, we changed the design to display rpm.

Week-12: Instead of generating clock frequency with using crystalize oscillator circuit, we used a NE555 timer IC and the generated signal has 750ms period.

Week-13: Clock set 750ms period with %50 duty to count rpm correctly. When clock connected to the counter the reset time was so small to observe on the BCD screen because it was changing instantly. We set an edge triggered circuit to increase time interval without spoil the rpm.

1. Introduction

We must overcome four major design challenges in making a DC motor speed controller and displaying rpm:

1. Error Signal Detection:

The output of the differential amplifier is called the error signal. The error signal is represented as given below. Error Signal can be produced as a difference between the output voltage of Pot and the output voltage of MMV.

$$ErrorSignal \ = V_{outPot} - V_{outMMV}$$

2. PWM Unit:

Pulse Width Modulation (PWM) is a method for controlling analog devices with digital outputs by generating discrete parts. Discrete parts determine as duty cycle which produced by a timer. With Half-Bridge Driver, the signal (generated pulses) transformed to DC form so that driver can control motor depends on the width of the pulse in a period.

3. Driving Motor:

DC motors could need high currents. If the motor is directly connected to the controller, it can be damage to controller the main purpose of using drivers is converting the low current which is coming from controller to high current. Then this high current used to supply motor. Generally, drivers work as a switch, if their input signal is high enough to open driver, a driver allows to supply the motor with supply voltage.

4. Displaying RPM:

RPM is the number of turns of the motor in one minute. RPM must be counted in the counter correctly. Counter adjusted with clock and edge triggered circuit. The display is driven by BCD to 7 segment decoder. Since this is 3-digit display, digital selection pins determine the order of digits. The display could be anode or cathode. Anode displays show the exact segments when their pins are high. Cathode displays show opposite segments when their pins are high. Anode and cathode displays can be converted from each other.

Following paragraphs summarize the necessary background information for the key technologies utilized in this project.

1.1 Monostable Multi Vibrator

They are kind of oscillators. They have one stable state. When they triggered, they generate pulses with a specified width. The frequency of the generated signal depends on the external RC value. The main purpose of the monostable vibrator in a circuit is generating pulses with changing the width of the output signal according to input signals frequency.

1.2. Pulse Width Modulation (PWM)

Pulse Width Modulation (PWM) is a method for controlling analog devices with digital outputs by generating discrete parts. This control is achieved by changing the duty cycle of the generated signal. Duty cycle is the name given the ratio of the on time of the signal to its period. This method generally used to control the intensity of LEDs and speed control of DC motors.

1.3. NE555 Timer

NE555 is a dedicated IC to produce necessary output waveform with time components. NE555 become the standard in the industry with time. Pulse width and frequency of the output waveform can be adjustable with resistors and capacitors. NE555 timer has three modes which are monostable, astable and bistable. The monostable mode used for time delays. Oscillating pulses can be generated in the astable mode. The bistable mode is acting like a flip-flop, switches the state of the output waveform.

1.4. Positive Edge Trigger

Edge triggered is a modification method to change the clock. Normally, clock changes when the signal is high or low, in the edge-triggered system clock changes while the state is changing.

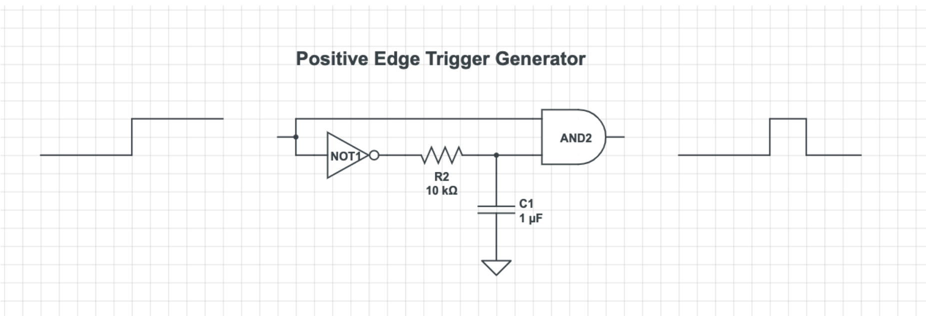

Figure 1. Positive edge trigger circuit

2. Technical Description

To drive the motor for the first time an initial output signal of the PWM generator must have almost50%duty cycles which can be adjusted with a potentiometer. For this situation, the potentiometer output voltage must be equal to 3.38V. Since there will be no output voltage from the monostable multivibrator, that voltage directly transmits into the PWM generator unit. Pulses are generated in this unit and their duty cycles depend on the input voltage. Generated PWM signal is sent to the driver, the driver works as a switch. When positive voltage arrives its input, it allows the drive its output pin with its supply voltage. If its input signal is a pulse, its output signal has the same frequency and duty cycle as an input signal. The only difference between input and output signal is the peak voltage.

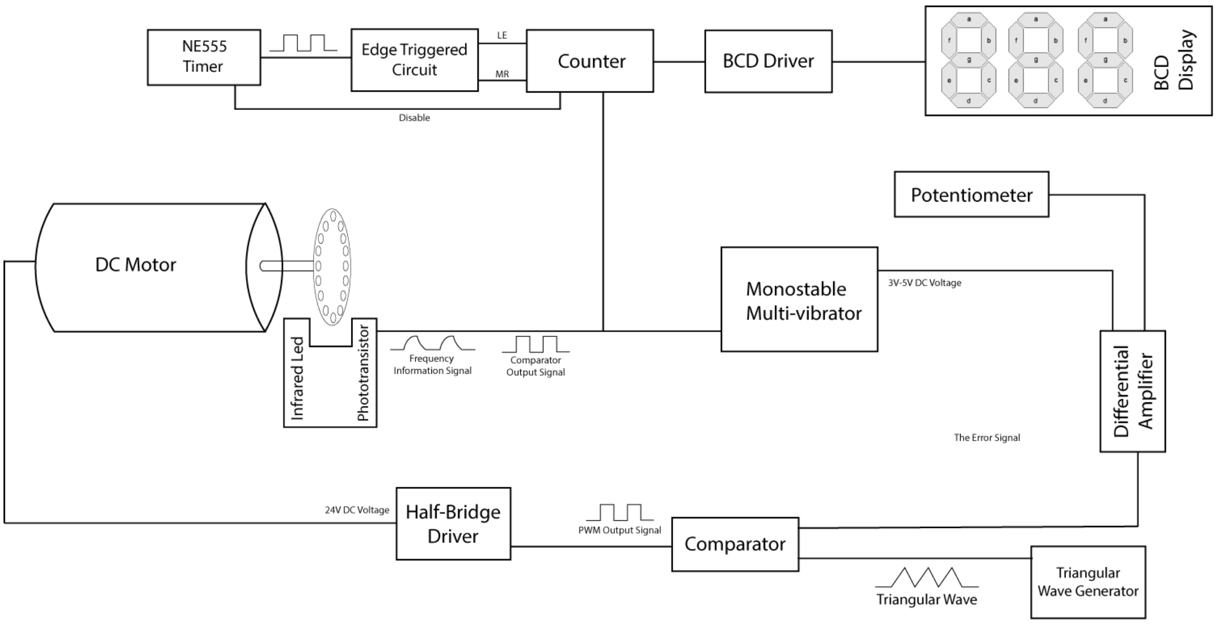

Figure 2. Block diagram of the DC Motor Speed Control Project

Perforated disc (16 holes) starts to turn with the motor. An Infrared led and phototransistor placed near the disc. Phototransistor detects 16 led lights in one tour of the motor and generates the frequency information signal. Then the monostable multivibrator is used to generate pulses. The generated pulse width proportional to the frequency of input signal and using by low pass filter, the Vrms value of pulses were obtained. At the output of the filter, DC voltage which is proportional to frequency is obtained. Potentiometer's output voltage and the output voltage of monostable multivibrator compared at the differential amplifier. Depending on the result, an error signal is generated. Then the motor is automatically accelerated or decelerated to reach the desired rpm.

The output signal of the phototransistor is also transmitted to the counter. NE555 works as a timer and generates a clock. This clock is used by the counter as a disable. A positive edge trigger located between timer and counter to delay the clock without affecting the rpm. With using BCD driver, the rpm displayed on the BCD.

3. Design Description

3.1. Error Signal Generation

It was generated by taking the difference of potentiometer signal and MMV signal. The output of the differential amplifier is called the error signal. The error signal is represented as given below. Error signal generation can be examined in four parts.

$$Error\ Signal\ = V_{outPot} - V_{outMMV}$$

LED – Phototransistor Circuit

An Infrared Led and Phototransistor are positioned face to face with a 5mm gap. A perforated disc placed in that gap. When the disc is rotating and the LED is always on, the phototransistor detects the light passing through the holes of a disc. When a phototransistor detects light, it generates current depends on the intensity. In our LED-phototransistor pair component amplify the current and turned to voltage. The output of this component is a fractured pulse wave. Peak voltage (VP) of this signal is nearly 5V.

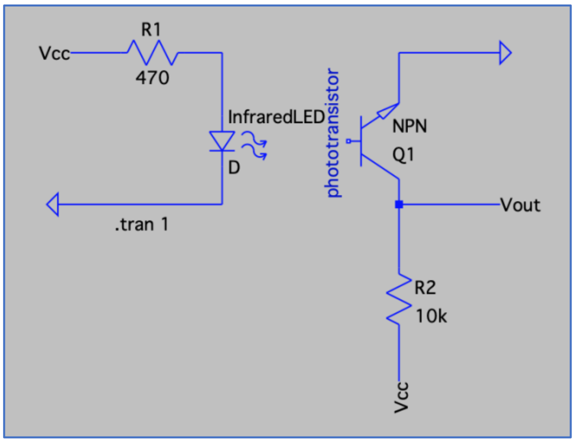

Fig3: LED-Phototransistor Circuit

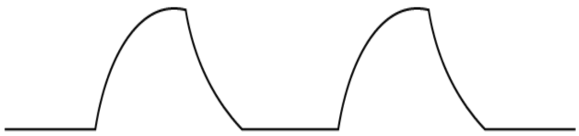

Fig5: Output of the phototransistor

LED-Phototransistor Circuit Design Targets			
Description of the design target	**Min.**	**Max.**	**Unit**
Input voltage V_{cc}	**4.7**	**10**	**V**
Diode Current	**10m**	**25m**	**A**
Output voltage V_p	**4.8**	**5.2**	**V**

Table 1. Design targets for the LED-Phototransistor Circuit

Comparator

The output of the phototransistor is a fractured pulse wave as shown in Fig3. The input voltage of MMV was modeled as a square wave while simulating. A comparator was used to get sharper rising edges and falling edges.
The aim of the comparator is reducing the error while circuit installation.

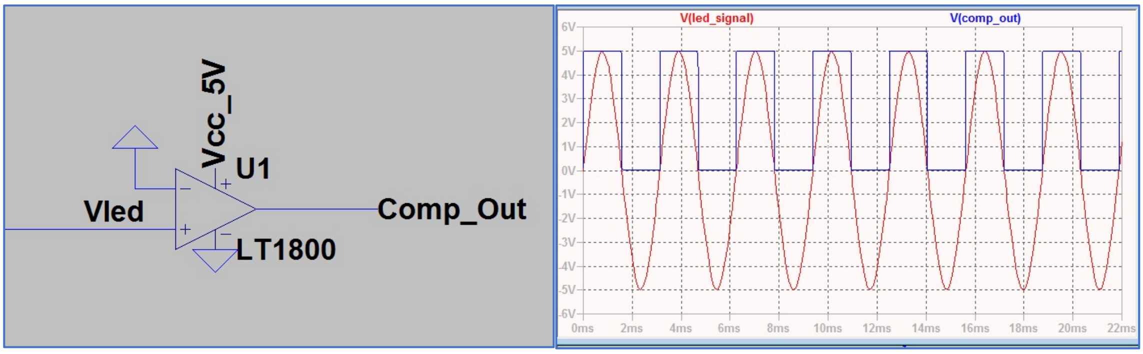

Fig6: Comparator Circuit and Output Signal

Comparator Design Targets			
Description of the design target	**Min.**	**Max.**	**Unit**
Input voltage	**4.8**	**5.2**	**V**
Output low voltage	**0**	**2.5**	**V**
Output high voltage	**4.5**	**5.1**	**V**
Output slew rate	**0**	**5.5**	**V/ms**

Table 2. Design targets for the comparator

Monostable Multivibrator

Monostable multivibrator generates the pulses which have regulated pulse width. Generated pulses' width change with the input signal's frequency, if the input signal's frequency increase, generated pulse width also increases. To obtain the dc voltage value equivalent of each pulse, the low pass filter was used at the output of MMV. Low pass filter cut off frequency calculation shown in figure 6. Expected f_c is 150Hz. With using a resistor (R2) as a 100kΩ and 1μF capacitor (C2) f_c is obtained 159Hz.

$$V_{out} = \frac{X_c}{X_c + R} \times V_{in}$$

$$\frac{V_{out}}{V_{in}} = \frac{X_c}{\sqrt{R^2 + {X_c}^2}}$$

$$\frac{1}{\sqrt{2}} = \frac{\frac{1}{\omega c}}{\sqrt{\frac{1}{\omega c}^2 + R^2}}$$

$\omega = \frac{1}{R.C}$ and $f_c = \frac{1}{2\pi RC}$

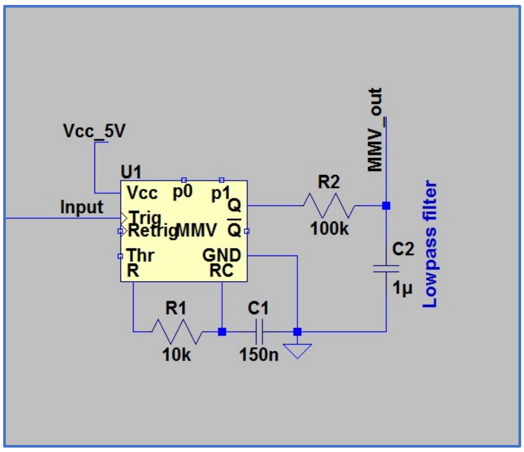

Fig 7: Low pass filter cut off frequency calculation Fig 8: MMV Circuit

Monostable Multivibrator Design Targets			
Description of the design target	**Min.**	**Max.**	**Unit**
Cut-off frequency f_c	150	160	Hz
Supply voltage	5	10	V
Output Ripple Voltage v_{rip}	0	30	mV

Table 3. Design targets for the monostable multivibrator

Differential Amplifier Circuit

Differential amplifier subtracts the voltage value of the output of MMW(V_{MMV}) from the voltage set by the potentiometer(V_{pot}). The output of this circuit part is called the error signal. If the error signal is positive that means motor's speed must increase. Otherwise, the error signal is negative then the speed of the motor must decrease. If the error signal is equal to zero, the motor is turning at the speed we want.

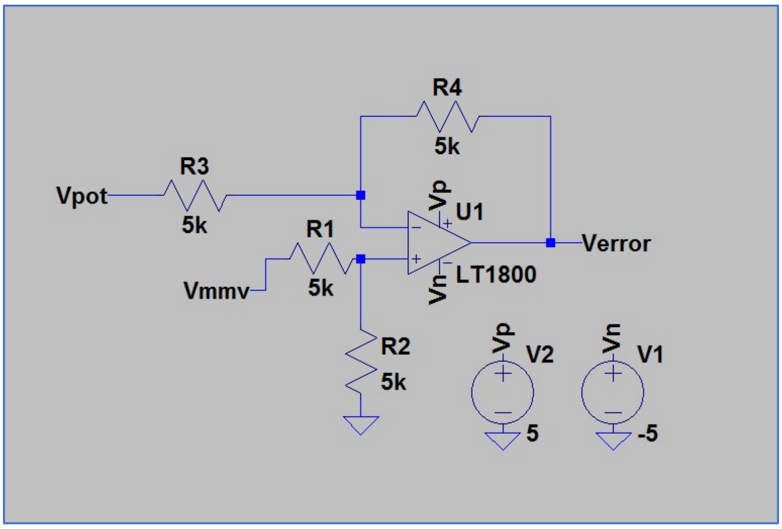

Fig 9: Differential Amplifier Circuit

Differential Amplifier Design Targets			
Description of design target	**Min.**	**Max.**	**Unit**
The output voltage of MMV V_{MMV}	1.64	4.4	V
The output voltage of Potentiometer V_{pot}	1.6	4.4	V

Table 4. Design targets for the differential amplifier

3.2. PWM Unit

The PWM unit is composed of an oscillator and comparator.

Upper op-amp circuit used as an oscillator. The oscillator creates triangular pulses. Their peak to peak voltage is 2.1V. Their calculations are given below. The output of the oscillator is fixed. The output of this op-amp connected to the second op amp's positive input. This op-amp used as a comparator to compare triangular pulse and error signal. The output of comparator gives pulses. The duty cycle of pulses depends on the value of the error signal. At the output of the comparator circuit, negative pulses are observed when the motor is rotating faster than wanted and their amplitudes are -5V. To obtain positive error value for all potentiometer levels, a 5V offset is applied to generated pulses. This process is called Pulse Width Modulation. This pulse signal is used to drive the motor and it is transmitted to Half-Bridge driver.

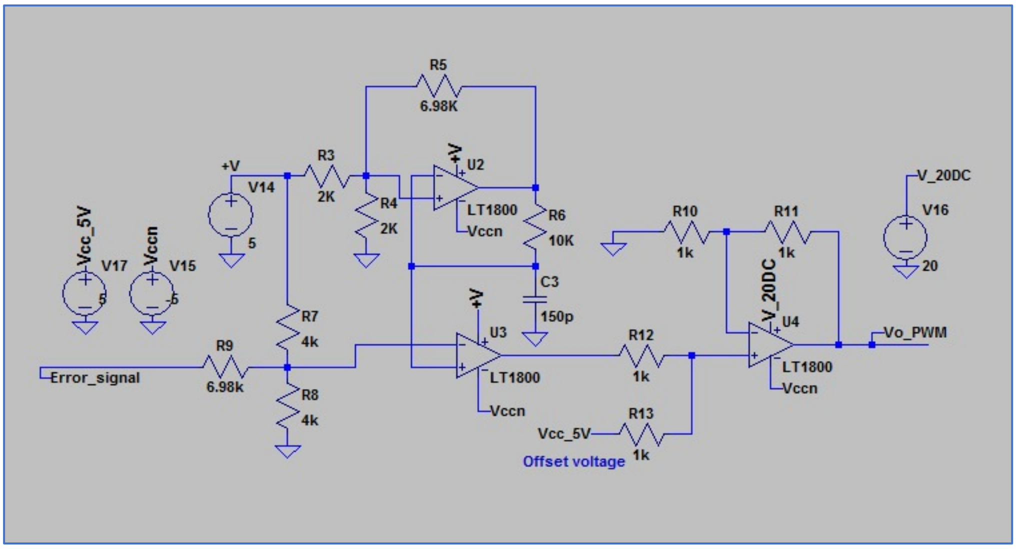

Fig.10: PWM Unit Circuit Design

PWM Unit Design Targets			
Description of design target	**Min.**	**Max.**	**Unit**
Duty cycle	0	100	%
The output voltage of PWM	0	10	V
The frequency of PWM Signal	900	1200	Hz

Table 5. Design targets for the PWM unit

3.3 Driving Motor

To drive the motor L298N dual full-bridge driver is used. It contains two full-bridge drivers. The full-bridge driver consists of two haft-bridge drivers. Full bridge driver allows turning the motor in different directions. In this project does not relate to turning direction so only one half-bridge is used. Bridges are composed of transistors. Transistors work as a switch. When they become on the situation, they allow passing supply voltage(V_{cc}) to the motor. They're on/off situation depends on the PWM signal.

Half-Bridge Driver Design Targets			
Description of design target	**Min.**	**Max.**	**Unit**
Input voltage	**0**	**10**	**V-peak**
Output low voltage	**0**	**1**	**V**
Output high voltage	**23**	**24**	**V**
Output duty cycle	**0**	**99**	**%**

Table 5. Design targets for half bridge driver

3.4 Displaying rpm

The purpose of this circuit part is displaying the number of turns of the motor in one minute. As mentioned, the rotating disc has sixteen holes, so every sixteen peaks of phototransistor signal represent one turn of the motor. The output of the phototransistor signal, which was named as a frequency information signal, transmitted to the 3-Digit BCD counter.

NE555 used as a timer to generate clock which has special value T=750ms with %50 duty cycle. This value selected because the counter counts the rpm 10 times smaller than the normal value. It can be directly printed on the 3-Digit BCD Screen. A positive edge triggered circuit located between timer and counter. The aim of this part is delaying the rpm on the screen without changing rpm. As the counter continues to count, it displays the old count until the next edge

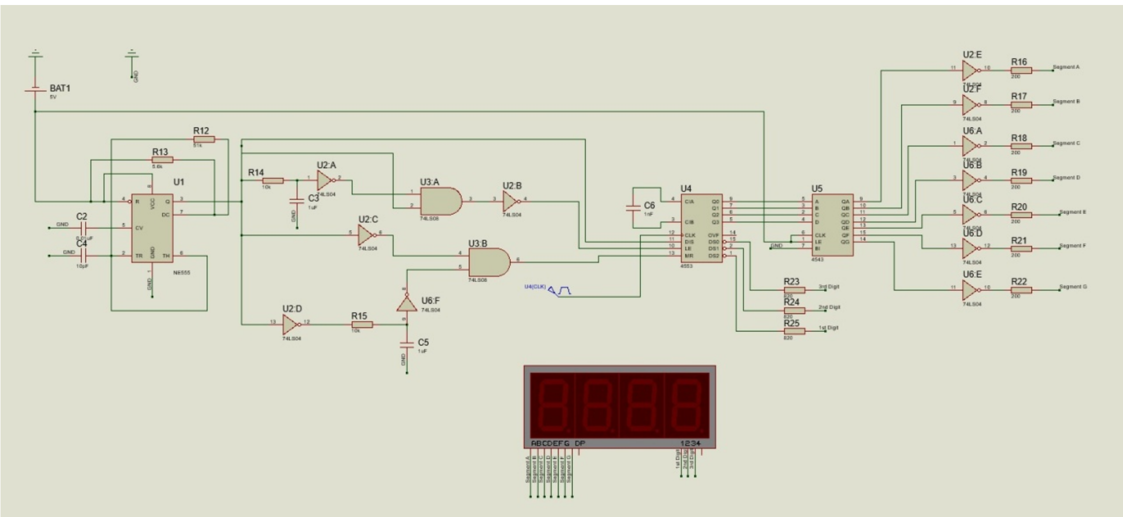

Fig. 11: Display Unit Circuit Schematic

NE555 Timer

The aim of using NE555 was to produce a square wave with a period of 750ms and a duty cycle of 50%. It is the clock of the counter and connected to the disable pin of the counter. Period and duty cycle adjusted by calculating R and C values in the formulas below.

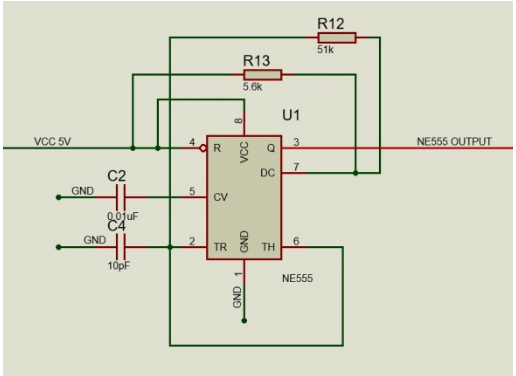

Fig. 12: NE555 Timer Circuit

Frequency of the output wave $(f) = \frac{1.44}{(R_1+2R_2)C}$

Period of the output wave $(T) = \frac{1}{f} = 0.694(R_1 + 2R_2)C$

Time High $(T_1) = 0.694(R_1 + R_2)C$

Time Low $(T_0) = 0.694(R_2)C$

$$Duty\ Cycle = \frac{T_1}{\mathrm{T}} \times 100$$

Displaying RPM Design Targets		
Description of the design target	**Value**	**Unit**
Frequency f	**1300**	**Hz**
Period T	**745**	**ms**
Duty Cycle	**%51**	
Time High T_1	**392**	**ms**
Time Low T_0	**353**	**ms**
Latch Enable Period	**745**	**ms**
Master Reset Period	**745**	**Ms**

Capacitor charging time

Charging equation = $\frac{2}{3}V_{cc} = \frac{1}{3}V_{cc} + \frac{2}{3}V_{cc}(1 - e^{(-T_c/T_a)})$ where T_c = charging time T_a = $(R_1 + R_2)$.C

To solve for T_c;

$$T_c = T_a \ln(2) = 0{,}693(R_1 + R_2).C$$

When the capacitor's charge reaches the limit $\frac{2}{3}V_{cc}$, it starts to discharge. It is discharging until it's charge reaches $\frac{1}{3}V_{cc}$.

$\frac{1}{3}V_{cc} = \frac{2}{3}V_{cc}(1 - e^{(-T_D/T_B)})$ where T_D =discharging time

$$T_B = R_2.\mathrm{C}$$

To solve for T_D;

$$T_D = T_B \ln(2) = 0{,}693(R_2).C$$

4. Test Results

4.1. LED-Phototransistor Circuit Design

LED-Phototransistor Circuit Design Results		
Design target	**Measured value**	**Unit**
Input voltage	5	V
Output low voltage	0	V
Output high voltage	4.96	V
Output duty cycle	65	%

Table 1. Test results for the led-phototransistor circuit

The measured output and input voltages were the same as the expected values. The current of the phototransistor could not be measured because the used component is covered. Also, the expected duty cycle of the output signal was around 50% but the measured value is larger. However, it does not affect the rest of the circuit and measurements.

4.2. Monostable Multivibrator Test Results

Monostable Multivibrator Test Results		
Design target	**Measured value**	**Unit**
Input voltage	5	V
Output low voltage	1.84	V
Output high voltage	5.04	V
Output min ripple voltage	5	mV
Output max ripple voltage	32	mV

Table 2. Test results for the monostable multivibrator

The external capacitor and resistance values did not change so, the timing of MMV did not change. However, the measured min ripple voltage did not same as expected. Measured ripple is higher than expected but there was no huge difference so, the effect was not observed.

4.3. Differential Amplifier Circuit Test Results

This part used to generate an error signal. Control signal which is adjusted by potentiometer is changing between 0-5V. While motor turning with 1200 pm error signal is 1.84V and for 3000V it is 4.96V. These values are larger than expected because to obtain minimum speed as 1200 rpm, the error is fixed to 1.80V. Also, while the motor is turning if the motor speed decreases because of external factors, as expected the increase was observed on the error signal.

4.4. PWM Generating Test Results

PWM Generating Test Results		
Design target	**Measured value**	**Unit**
Triangular wave min voltage	**560**	**mV**
Triangular wave max voltage	**2.64**	**V**
Triangular wave frequency	**986**	**Hz**
Error signal min voltage	**1.84**	**V**
Error signal max voltage	**4.96**	**mV**
Output min duty cycle	**40**	**%**
Output max duty cycle	**100**	**%**

Table 3. Test results for the PWM generating part

The peak-to-peak voltage of the triangular wave is not large because of this the speed changing is so sensitive. V_{pp} should be larger. The frequency of the triangular wave was expected to be 1kHz but the value was 1.4% lower. However, it does not affect much the circuit because for low rotating speed no need to a higher frequency.

4.5. Driver Output Test Results

Output peak voltage was the same as supply voltage and also the duty cycle and frequency were equal to the generated PWM signal as expected.

4.6. Displaying rpm Test Results

Displaying rpm Test Results		
Description of the design target	**Value**	**Unit**
Frequency f	**1250**	**Hz**
Period T	**405**	**ms**
Duty Cycle	**52**	**%**
Time High T_1	**413**	**ms**
Time Low T_0	**366**	**ms**
Latch Enable Period	**800**	**ms**
Master Reset Period	**800**	**ms**

Table 4. Test results for displaying rpm part

The Ton value is 25ms more than the value which we calculated in the design description part. Latch enable period and reset period increased 50ms because they depend on the period. This situation increased the margin of error in the displayed rpm.

5. Conclusion

DC motors are widely used in the industry. The control of the power and speed of the motors is an important criterion. We wanted this project because it contains more than one subject such as feedback control and PWM.

After the first design of the project, we encountered the first problem. It was about the error signal. We had completely misunderstood the generating of the error signal. Instead of taking the difference of MMV output signal with a control signal, we used the motor input signal. After correcting our error, the error signal was generated as expected. Another changing in the first design is an infrared led-phototransistor circuit. In our design, the output signal of phototransistor was amplified and filtered, to generate a square wave, but the output signal of the phototransistor device does not need amplifying or filtering. The output was a 0-5V pulse so that we could directly use it. Then we started to research ways to generate PWM signal because the PWM signal was a new concept for us. We decided to generate a PWM signal by comparing the error signal with the triangular signal. To generate the triangular wave relaxation oscillator circuit was used. Then the necessary calculations were done to generate a signal with 1 kHz frequency. Unfortunately, the peak-to-peak voltage was small, because of this system is very sensitive. The small changes on the control signal which is generated by using potentiometer cause large changes in the duty cycle of the PWM signal. If we used 10V at the input of op-amp instead of 5V, according to the simulation result, we could get 1.3V larger Vpp voltage. The next step was comparing the triangular wave and the error signal. In the beginning, to compare signals LM393 IC was used but because of misconnection, IC was damaged. There was no time to buy a new IC, so we used to LM741 op-amp IC. To get rid of the negative pulses, the diode was placed to an output of the op-amp. Thus, we get the expected PWM signal.

BCD screen part was also a new concept for us. We changed the idea of counting rpm or rps several times. As a result, we decided on rpm. To count rpm, the first challenge is determining the time period for desired rpm levels. We do too many calculations for the finding accurate period, but our professor’s suggestion was better. We can count the rpm very accurate in the 750ms period. NE555 timer is used for generating this clock. The second problem was creating time delays. We start with the idea of using flip-flops, then we find a new solution. The solution is using edge-triggered circuits. Positive edge triggered circuit didn't affect the counter at the same time while providing us the time delay, we wanted. The final problem was the type of BCD screen. We had the cathode BCD screen. The cathode displays invert the data which comes from the BCD decoder. After we get segmentation data for BCD screen, we used not gate to invert the data to display on the BCD screen.

6. Component List

Component description	Part Number	Manufacturer	Supplier
DC Motor	**SY28 0752045**	STmicroelectronics	Electronics Lab.
Operational amplifier	**LT1800**	Linear Technology	Electronics Lab.
Npn-BJT	**BC237**	Texas Instruments	Electronics Lab.
H-bridge driver	**L298n**	Stmicroelectronics	Electronics Lab.
Monostable Multivibrator	**74LS123**	Texas Instruments	Electronics Lab.
Timer	**NE555**	Texas Instruments	Electronics Lab.
Not gate	74LS04	Texas Instruments	Electronics Lab.
And gate	74LS08	Texas Instruments	Electronics Lab.
3-Digit BCD Counter	CD4553	Sycelectronica	Electronics Lab.
BCD to 7 Segment Latch Decoder/Driver	CD4543	Texas Instruments	Electronics Lab.
3-Digit BCD Screen			Electronics Lab.

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