Lab #7 Servo Motor Control

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1. Objective

The aim of this lab experiment is to build the complex circuit arranged in Figure 1 capable of determining and controlling the speed of an electric servo motor. We will achieve this objective by bringing together our accumulated knowledge and understanding of different circuit elements and components such as Diodes, OpAmps, Counter, D-Latch, RC-Combinations, and more.

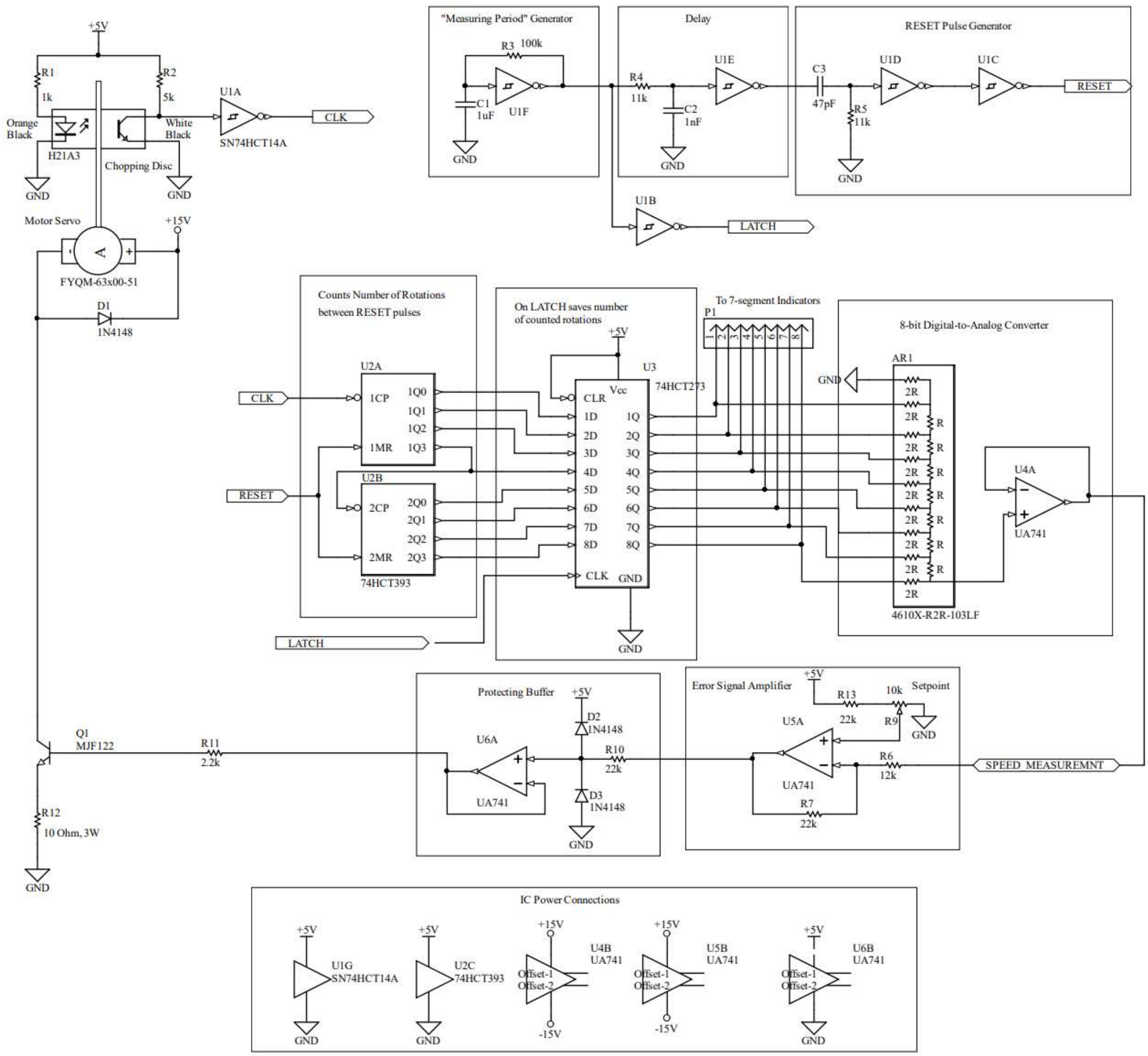


Figure 1. The setup of the servo control motor **Taken from the Lab7 Manual*

2. Background

As discussed, the objective of this lab experiment is to construct a servo motor control circuit. Such a circuit utilizes a feedback loop similar to one seen in the diagram below in Figure 2 to adjust one or more specific parameters to yield the desired output. In our case, we are attemting control the rotation frequency of an electric motor by adjusting the electrical current supplied through the motor.

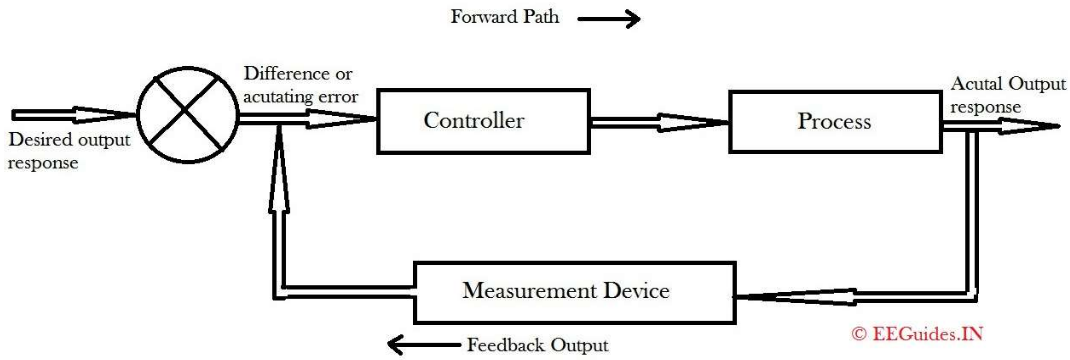


Figure 2. Feedback Control Loop Example

The circuit of this lab is mainly composed of five different components which come together to form and operate the servo motor:

- The Latch and Reset generators
- Counter and D-Latch sections
- An 8-bit Digital to Analog Convertor
- Motor Sensor and Motor Drive
- Error Signal Amplifier

The Latch generator will be creating a square wave signal which is fed to the D-Latch, enabling the D-Latch to store counter output for every rise and fall. The Motor Drive has a disk attached on it with a single slit and as the disk rotates, the slit will pass over an LED. When the slit passes over the LED, a photo transistor will be triggered, generating a clock (CLK) pulse. Our Counter will count the pulses between the Reset pulses generated by the Reset generated seen in Figure 1. The signal is stored on an 8-bit D-Latch and also displayed on a two digit 7-segment display. An 8-bit DAC will convert the digital signal to an analog signal which will be compared to a set voltage. Finally, the error is amplified and the amplified error output will be used to control the current to the motor by a power transistor.

**Adapted from the Lab7 Manual*

3. Troubleshooting

Problems encountered and the troubleshooting steps taken during the lab will be reported and discussed throughout the lab report within the corresponding and approperiate sections where the problems were discovered.

4. Experiment

4.1 Schmidt-Trigger Inverters

We will first explore one of the key circuit elements we will be using in our motor control circuit. An inverter is a digital operator which inverts a given digital signal from a low to high and vice versa. A specific type of an inverter is one that inverts the signal at different thresholds depending on the previous state or the history of the signal. Such an inverter is called a Schmidt-Trigger inverter with hysterosis.

To observe this effect, we construct the circuit in Figure 3.

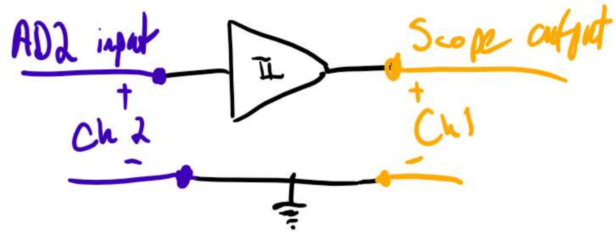


Figure 3. Schmidt-Trigger Inverter Circuit

We will be using a 74HC14A IC chip wich includes 6 such inverters. From the 74HC14A IC chip datasheet, we reference the pin orientation in Figure 4 where each digit represents a Shmidt-trigger inverter. We used the first inverter and all other inverters in the circuit were grounded.

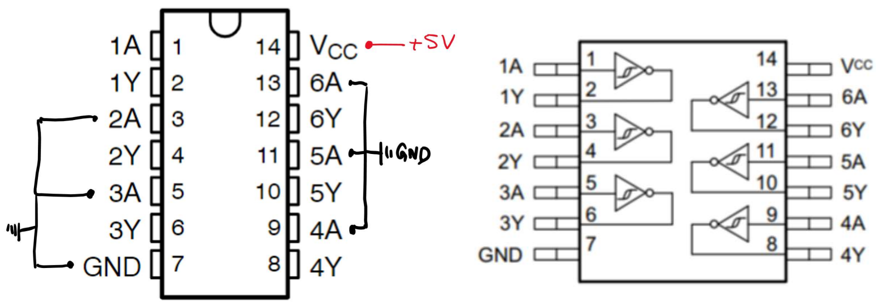


Figure 9. Pinout diagram of 74HC14N (On the right, you can see the orientation of the Schmidt-trigger invertors)

Plotting the inputs and outputs from our circuit in Figure 3 on Scope with WaveForms, we observe that the Signal inverts from High to Low at a different voltage compared to inverting from Low to High. This is visible in our scope readings in Figure 4 below.

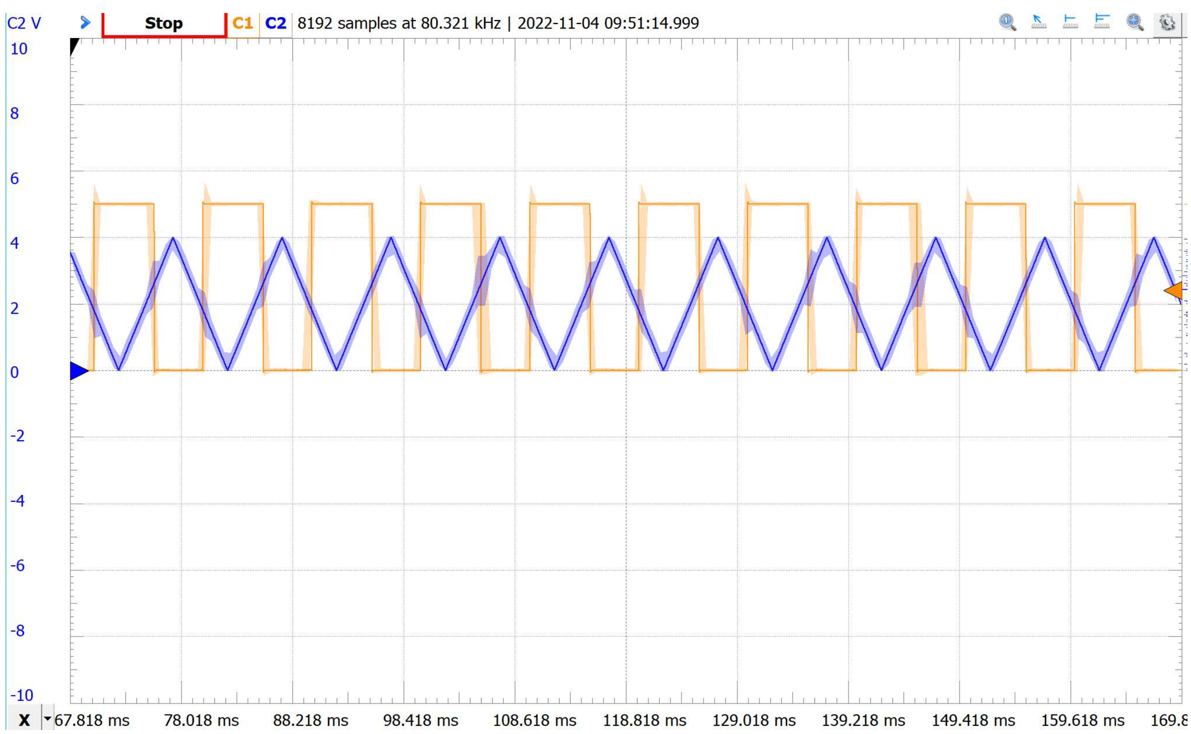


Figure 5. Input and Output to Invertor with hysterosis on Scope

To better visualize this consideration of the history of the signal, we use WaveForms to create an X-Y Plot to plot the input and output voltages of the invertor. In Figure 6 below, the input voltage is displayed on the x-axis and the output voltage is displayed on the y-axis. On a side note, the figure of the plot in Figure 6 is also used as the symbol for these types of invertors.

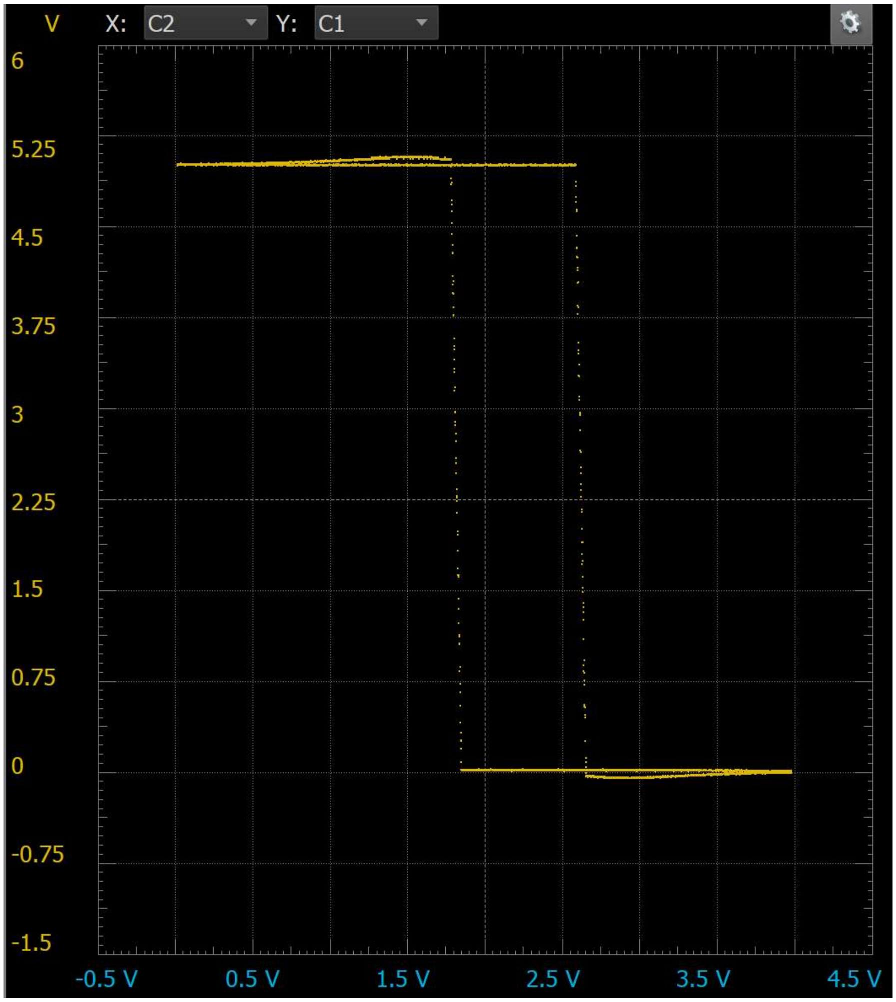


Figure 6. The hysteresis invertor Input (x-axis) vs Output (y-axis) plot

As it is clear in Figure 6, the output changes at two different thresholds. However, we can not achieve an accurate reading to find the values of the threshold in this plot; therefore, we will turn back to our Scope readings. Using the Y Cursors function of the Scope, we can find the voltage thresholds at which the Schmidt Invertor inverts a digital signal.

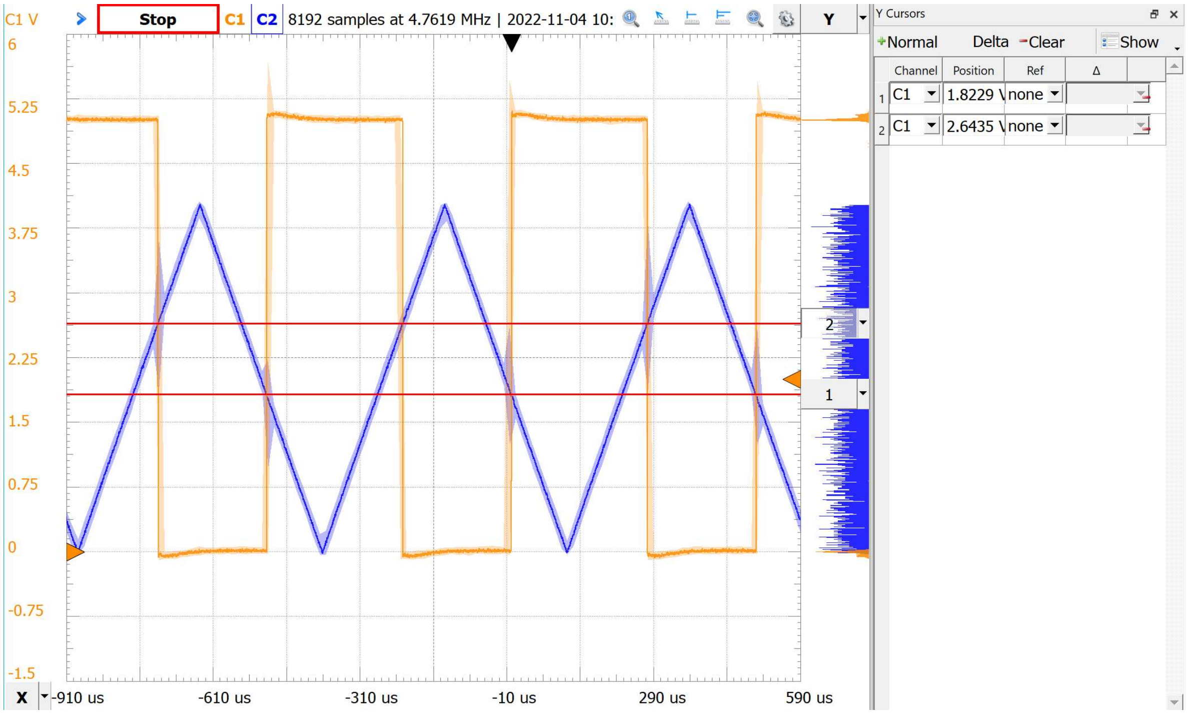


Figure 7. Input and Output to Inverter with hysteresis on Scope with Y Cursor

In Figure 7, we make sure the two channels have the same resolution. Then through out Cursor readings we can see that the Schmidt-trigger Invertor reverses the signal at ~1.823 V when input is going from high to low and at ~2.644 V when input is going from low to high.

As a result of the Schmidt-trigger inverters' ability to take into account the history of the signal, these invertors can be utilized to provide *noise immunity* as they will only invert a signal when it is above a certain threshold and will "filter" any weaker signals below that threshold that could be the result of circuit elements' imperfetions and signal impurities.

Troubleshootings in 4.1

Problem 1: The output of the Schmidt-trigger input was sometimes as expected, but often specially when left for a few seconds would display a constant voltage of 5 Volts or a High state.

Troubleshooting Steps:

- The invertor outputs a High when the input is a Low, so we first assumed that the input was turning off that the caused the output to be a constant High. So, we checked if the AD2's Wavegen was on and the AD2's was always supplying the square wave.
- After asking our TA, we realized that all other invertors in the 74HC14N chip must be grounded.
- Upon grounding the inputs to all invertors that were not used, the problem was resolved and the expected output was now maintained.

4.2 Latch, Delay, and Reset Pulse Generators

4.2.0 Circuit Diagrams and Construction

To begin constructing our motor control circuit, we will begin by constructing the Period Generator and LATCH in Figure 8 part (a), Delay Generator in Figure 8 part (b), and the RESET Pulse Generator in Figure 8 (c) using a 74HC14N IC chip. Figure 9 shows the Pin out diagram of the 74HC14N. The pins used from the chip correlating with the invertors in the circuit diagram are labled in Figure 8.

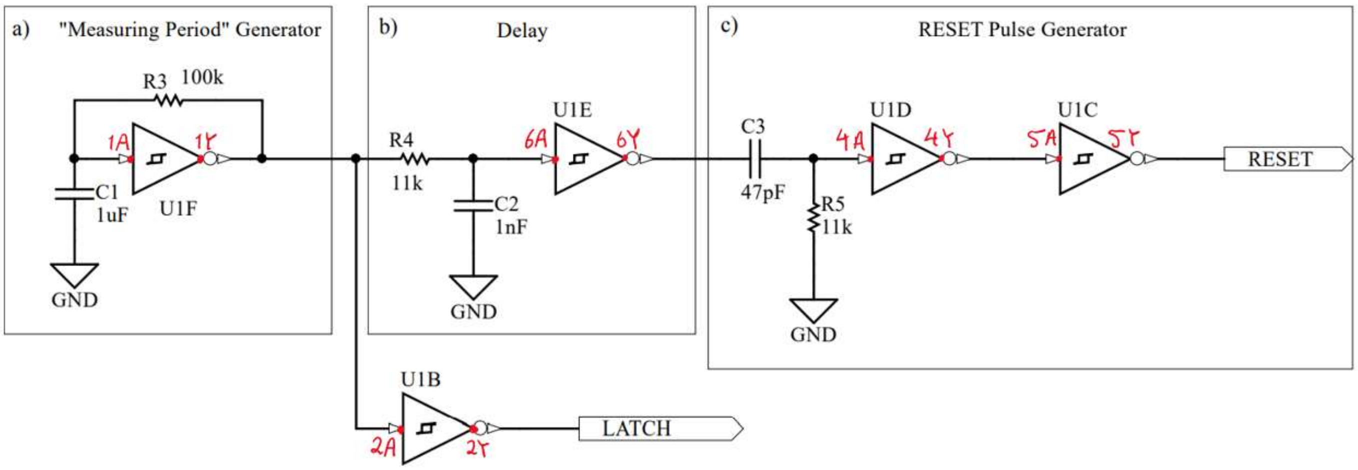


Figure 8. a) Measuring Period Generator, b) Delay Generator, and c) Reset Pulse Generator

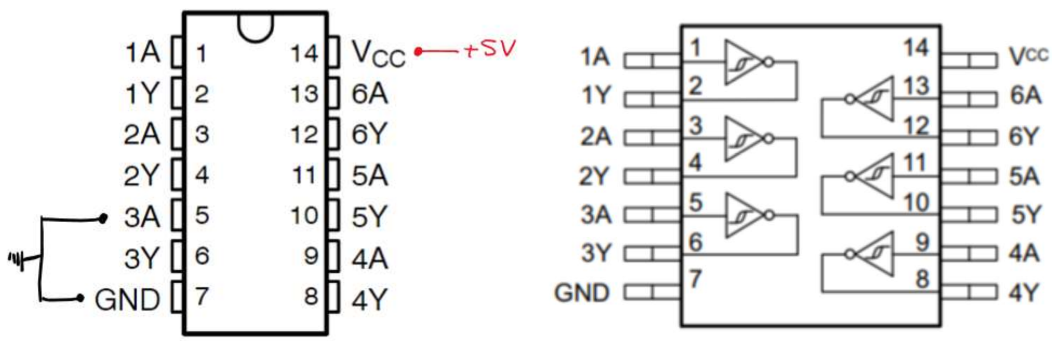


Figure 9. Pin out diagram of 74HC14N (On the right, you can see the orientation of the Schmidt-trigger invertors)

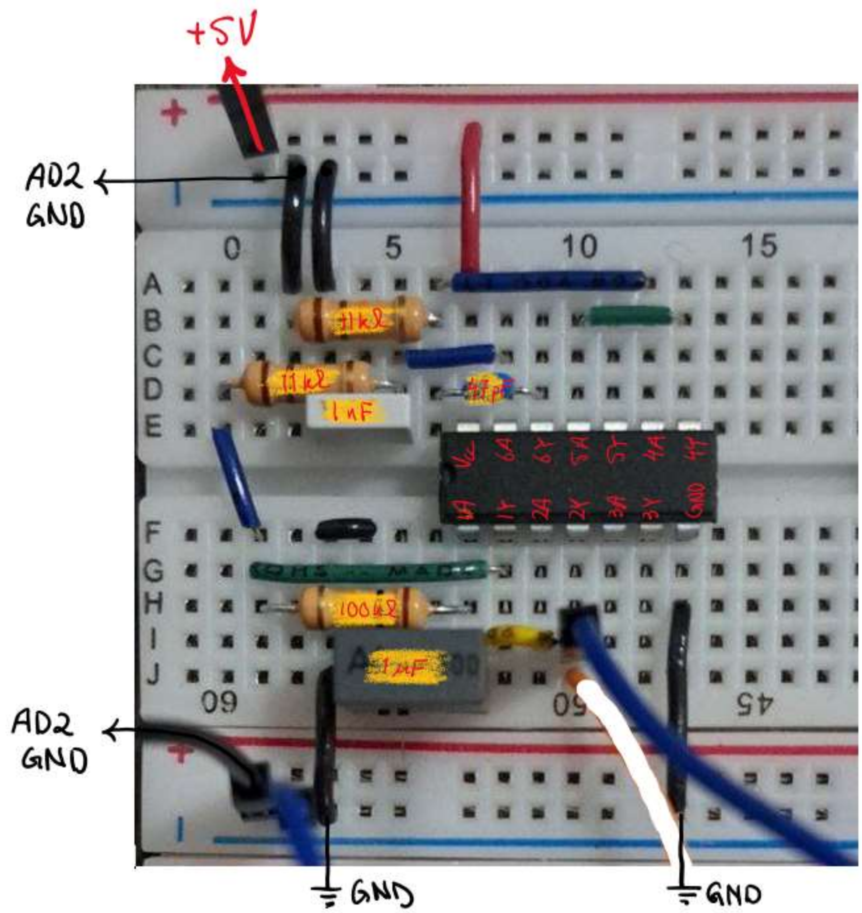


Figure 10. Assembeled Measuring Period Generator, Delay Generator, and Reset Pulse Generator

4.2.1 Measuring Period Generator and LATCH signal

In Figure 10, we can see the output of our Measuring Period Generator on the scope, which is the output from the invertor U1F in Figure 8 (a).

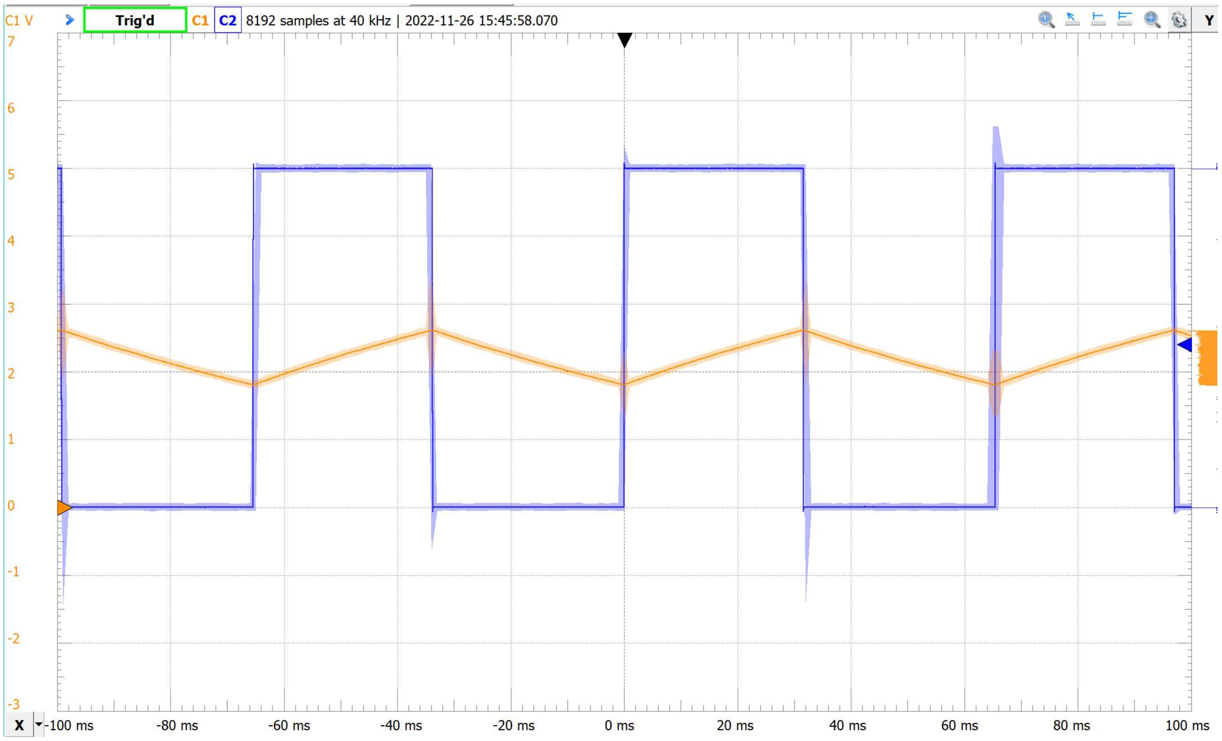


Figure 11. Square wave output of the Mesuring Period Generator (Blue) and the voltage across the capacitor (orange).

As we can observe in Figure 11, the output of the Measuring Period Generator is a square wave, and the LATCH signal will be this signal inverted. We explain how the generator works with the following scenario:

Please note all elements referred to are those in Figure 8 (a).

- Let us assume at t=0, the voltage across the capacitor C1 in Figure 8 (a) is zero volts; therefore, the input to inverter U1F is a Low signal.
- The Low signal is inverted into a High signal and after a drop across the R3 resistor falls on the C1.
- Slowly, the capacitor C1 charges and rises to a higher voltage obeying the time constant = R3*C1.
- When the voltage across C1 rises above the 2.644 V threshold, the inverter's output turns to Low.
- With the output of U1F being Low or 0 V, our C1 wich was previously charged begins to discharge until it passes the other threshold 1.823 V.
- When the voltage across C1 passes this threshold, the output becomes a High once again
- As this cycle repeats, a square wave is generated by the inverter's output which is inverted one more time by U1B and gives us the LATCH signal seen in Figure 10.

4.2.2 Delay Generator

Next, we build the Delay Generator in Figure 8 part (b). The delay generator section allows the LATCH signal to be grabbed or counted by the counter before there is a RESET signal. The delay generator works by adding an extra time constant which extends the signal since the added RC circuit will take time to convey the voltage signal to the next module.

We can observe this delay by displaying the LATCH signal (pin 2Y in Figure 10) as Channel 1 (Orange) and the output of the Delay Generator Module (pin 6Y in Figure 10) as Channel 2 (Blue). At first, they seem identical, but when zooming in and increasing the time scale, we can see the delay in Figure 12 below.

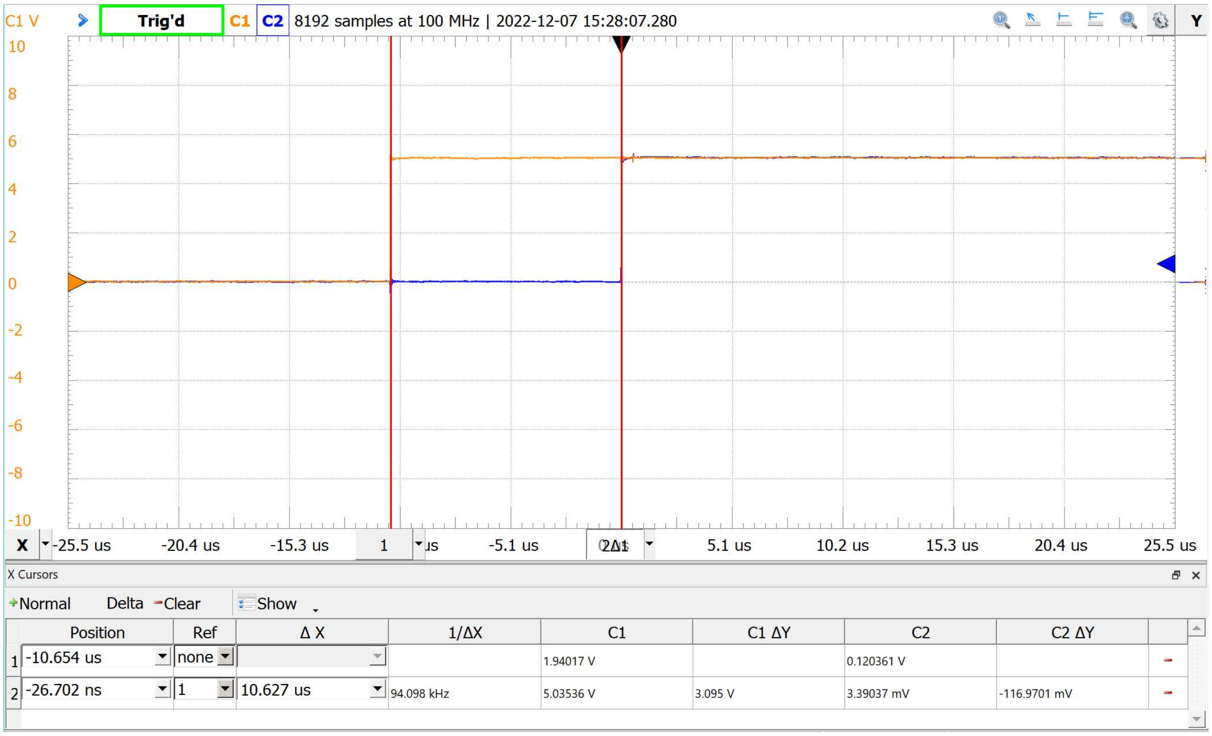


Figure 12. Output of the Delay Module Generator (Blue, and

We can theoretically calculate this delay using the given resistor and capacitor values in Figure 8 (b).

R4 = 11 kOhm; C2 = 1 nF

$$\text{Expected Delay} = \text{RC} = 11\,k\,\Omega * 1\,n\,F = 11\text{ us}$$
$$\text{Measured Delay} = 10.627\text{ us}$$

We measure delay in our circuit using the X-Cursurs of the Scope in Figure 12 and it is approximately 10.627 us which is close to our calculated theoretical value.

4.2.3 RESET Generator

Finally, for this section, the Reset generator, generates pulses that will reset the counter which comes later through the circuit. To see how the Reset Generator works, we trace output of the generator with the signal before the delay in Figure 13 below which displays the LATCH signal (pin 2Y in Figure 10) in Orange and the Reset Pulses (pin 5Y in Figure 10) in Blue.

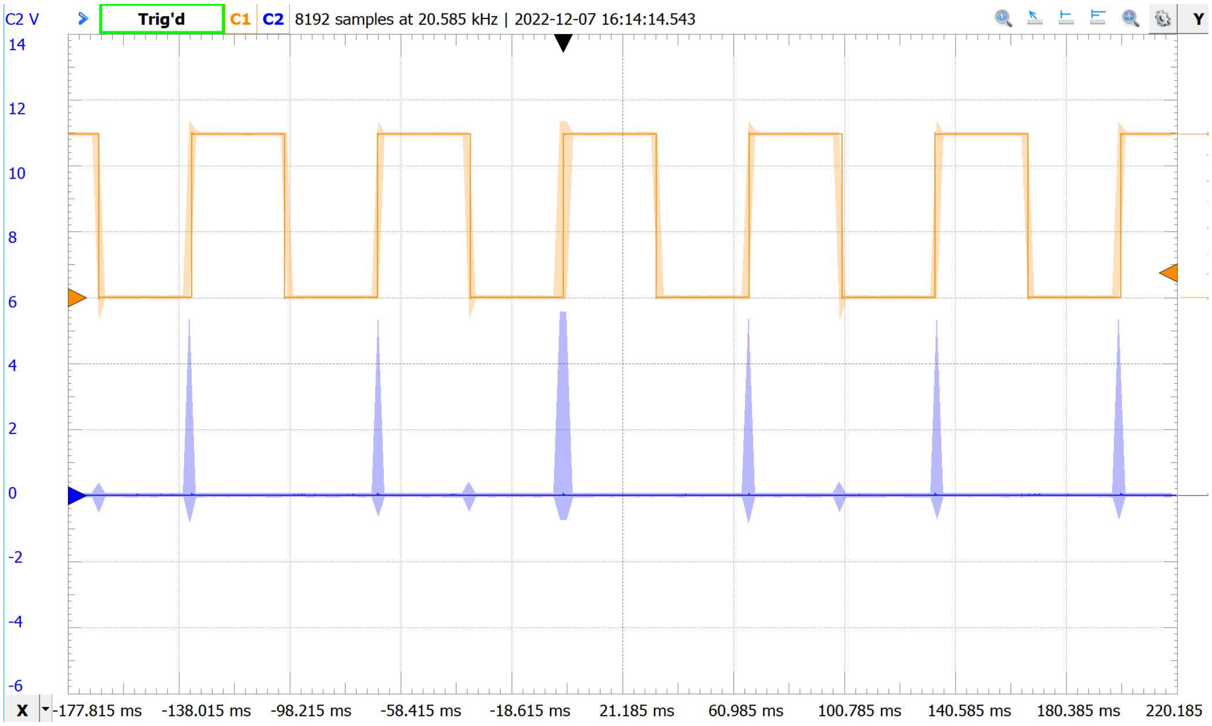


Figure 13. LATCH signal (Orange) in comparison to RESET signal (Blue). Note that the Orange trace is diplaced by 6 units to the up.

From Figure 13, we can observe that a RESET signal is generated every time that the LATCH signal goes from low to high, of course with the ~10 us delay; however, the signal seems to be very faint at first glance. This is because the signal is very short lived and if we zoom in and increase the time scale, we can see the signal that goes from 0 to 5 Volts in Figure 14 below.

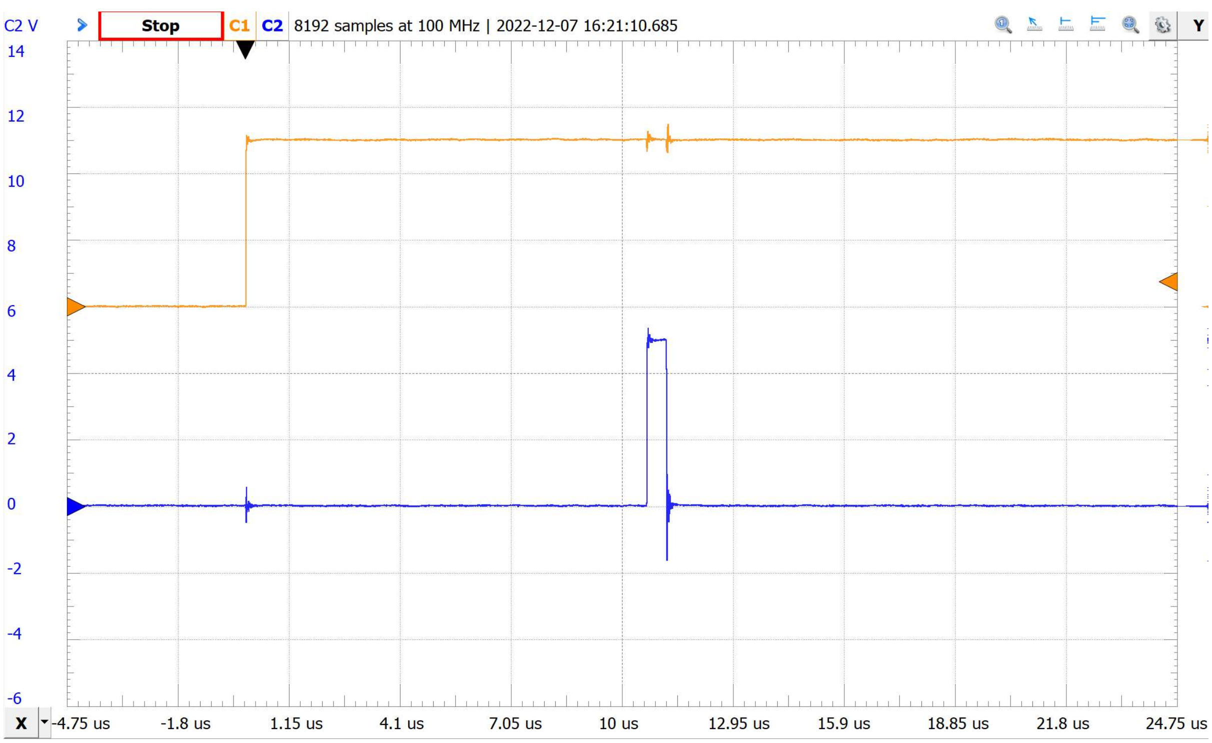


Figure 14. LATCH signal (Orange) in comparison to RESET signal (Blue). Zoomed in to smaller time scale.

In Figure 14, we can see that the RESET signal goes up from 0 to 5 Volts. Further, we see that the RESET is generated slightly after the LATCH goes up from 0 to 5 Volts which accounts for the delay generated in the previous circuit section. We use Scope's X-Cursurs and Delta function to measure the RESET signal.

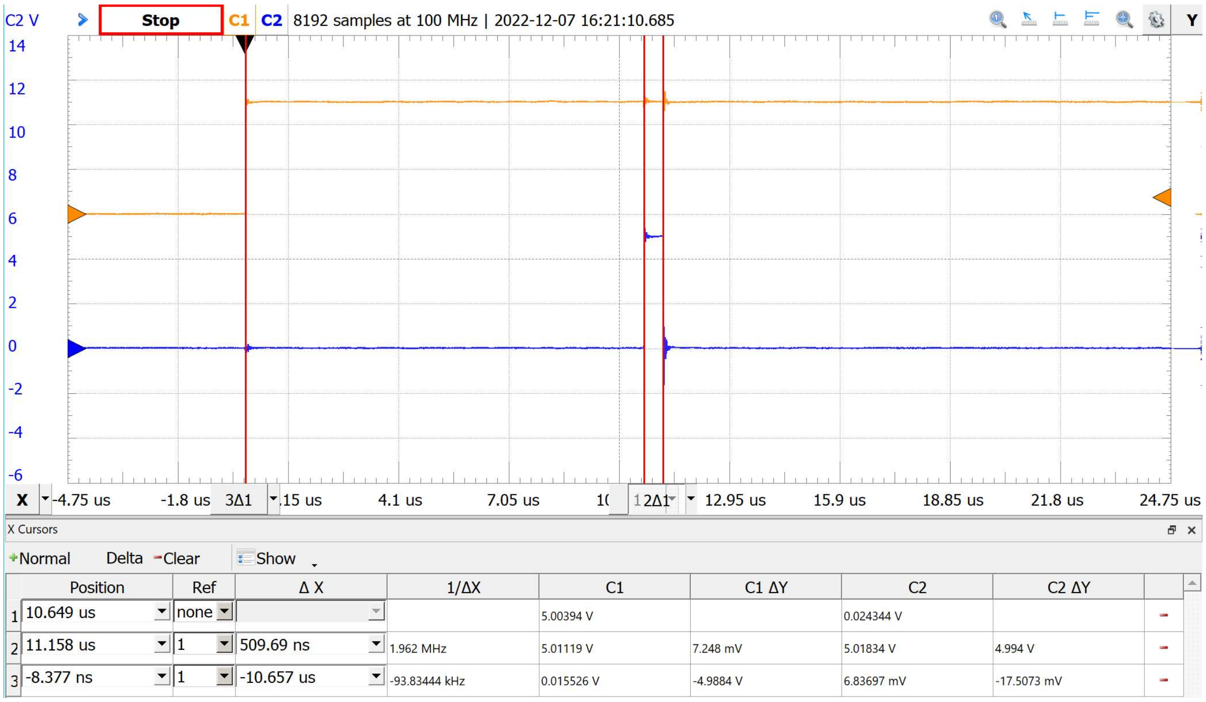


Figure 15. LATCH signal (Orange) in comparison to RESET signal (Blue). Zoomed in to smaller time scale and measured with Cursur.

The RESET generator creates short pulses or a square wave signal with a very short duty cycle by using a very small capacitor that will quickly discharge.

We can again calculate the theoretical length of this RESET signal using the given resistor and capacitor values in Figure 8 (c).

R5 = 11 kOhm; C3 = 47 pF

$$\text{Expected Delay} = \text{RC} = 11\, k\Omega * 47\, pF = 0.517 \text{ ms}$$
$$\text{Measured Delay} = 509.7 \text{ ns} = 0.5097 \text{ ms}$$

Troubleshootings in 4.2

Problem: When measuring the RESET signal, I initially only had the same Delay signal, and there were no Reset pulses.

Troubleshooting steps:

- I first checked that I had put in the correct resistor and capacitro, and I had.
- I then checked if my wiring was right and I had mistakenly connected the output of the delay to the ouput of the invertor UD1 instead of the input. I reconnected the wire and this solved the problem and I had the pulses.

4.3 Counter, D-Latch and DAC

4.3.0 Circuit Diagrams and Construction

Continuing our motor control circuit construction, we will set up the Counter and D-Latch modules of our circuit from the circuit diagram in Figure 16. Note that the pin numbers on the circuit diagram will be the same on the corresponding IC chip. For example ,1CP on circuit diagram in Figure 16 corresponds to the 1CP pin of the 74HCT393 pin-out diagram in Figure 17.

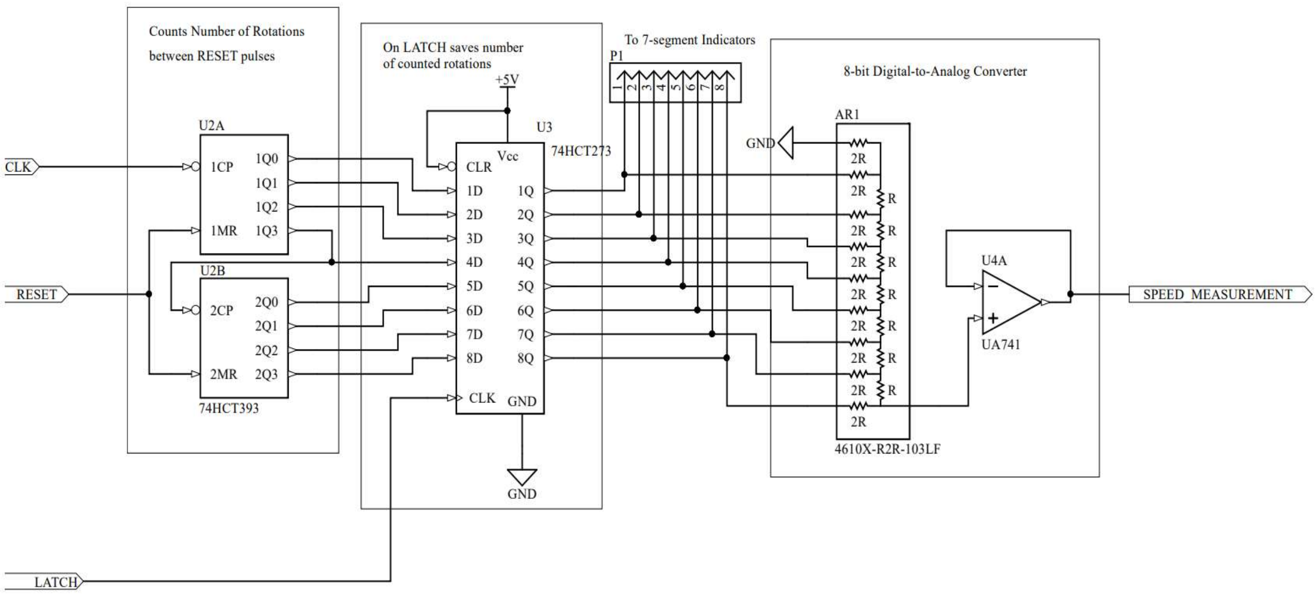


Figure 16. Counter, D-Latch, and DAC Circuit Diagram

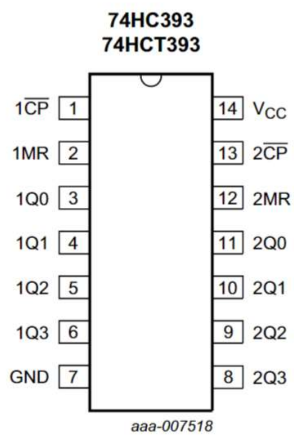


Figure 17. Pinout diagram of the Counter (74HC393)

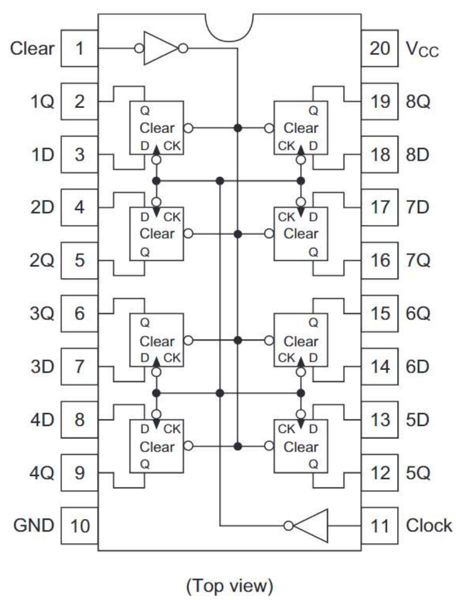


Figure 18. Circuit and Pinout diagram of the Octal D-Latch IC (74HCT273)

We construct the circuit in Figure 16 on the breadboard and the result is shown below in Figure 19.

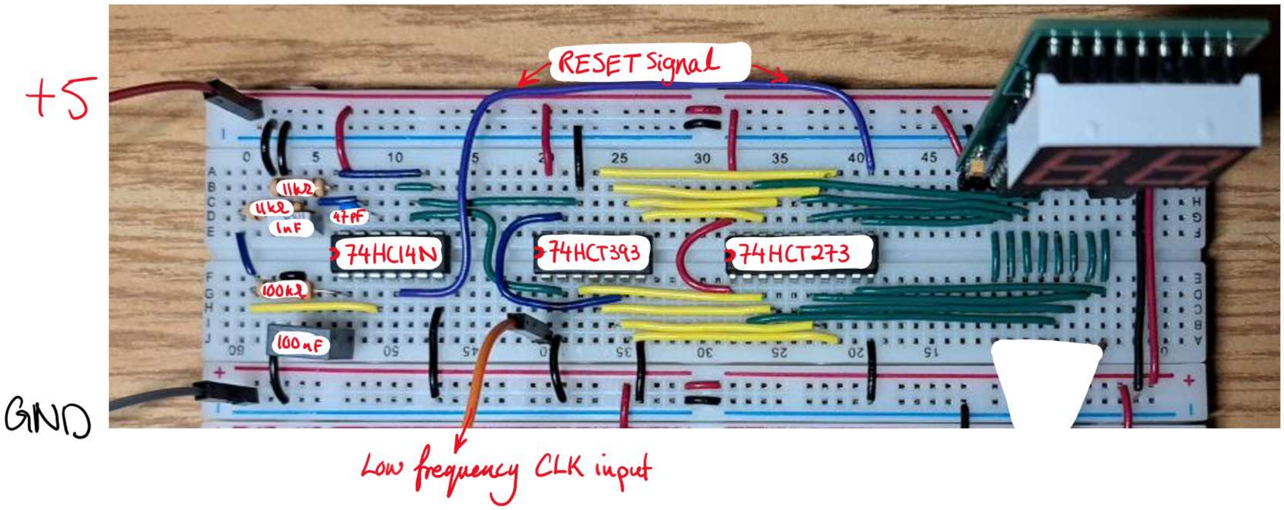


Figure 19. The Counter and D-Latch constructed on breadboard

4.3.1 Counter and D-Latch

To test our circuit, we have grounded the Reset pins of the counter as seen in Figure 19 with the black wires in rows 39 at the bottom and 22 at the top of the 74 IC chip. This way the reset pulses are not floating and will not disturb our count displayed on the 7-segment display.

Next, we connect the LATCH output from our previous section to the clock pin of the D-Latch as instructed in the Figure 19 circuit. For the CLK input to our counter, since we have not constructed the motor sensor and don't have a CLK signal, we will use WaveForms' Patterns function to generate a low frequency square signal.

Figure 20. Low Frequency CLK signal generated by AD2

With this low frequency CLK input from the AD2, the counter begins counting and the counts are displayed on the 7-segment display. We grab a reading from the display in Figure 21 below.

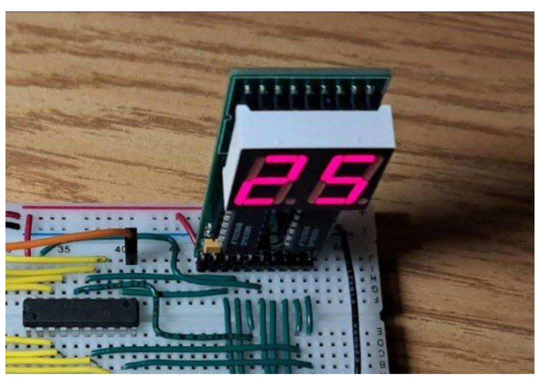


Figure 21. A count reading grabbed from display

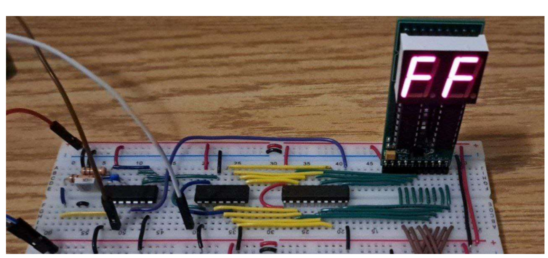


Figure 22. FF reading of the count grapped from display. Taking the picture at the exact time was extremely hard. Reduced the frequency to 0.1 Hz to catch it. :)

With the 7-segment display in Figure 22, we confirm that the counter counts the CLK inputs as the display functions and it counts upto FF wich is hexacode for 255 in decimal values. This is because our counter is only an 8-bit counter and the maximum decimal value that can be represented by 8 bits is 255.

As we've learned in previous experiments, the counter works by storing the number of times a CLK signal is pulse is generated. In other words, the counter increases count for every rising edge of the CLK signal that is given to it.

The 74HCT273 IC chip or the Octal D-Latch which contains 8 D-Latches captures the number of counted rotations and holds on to the count. The Octal D-Latch stores the rotation count by holding the state of each of the 8 bits outputted by the counter (74HC393). We have connected the CLR (pin 1) of the D-Latch (74HCT273) to the 5V input because the D-Latch should always be holding the counts outputted by the counter and should not reset independently of the counter, so by keeping the CLR always in a High state, we prevent the D-Latch from clearing the stored count.

4.3.2 DAC and Buffer

Our DC motor that we aim to control the speed for is an analog device. As such, in our control feedback loop, we must compare the current run through the motor with an analog signal; therefore, we must convert our digital count of the number of rotations to an analog signal, which will be our "Speed Measurement" signal. To achieve this, we use a 4610X-R2R-103LF, a Digital to Analog Convertor (DAC) which is an R2R resistive ladder, and connect the output of the Octal D-Latch to the DAC according to the circtuit diagram in Figure 16. We next connect the ouput to an Op-Amp according to the circuit diagram in Figure 16. We use the UA741 IC chip which houses the Op-Amp and has a pinout configuration shown in Figure 23.

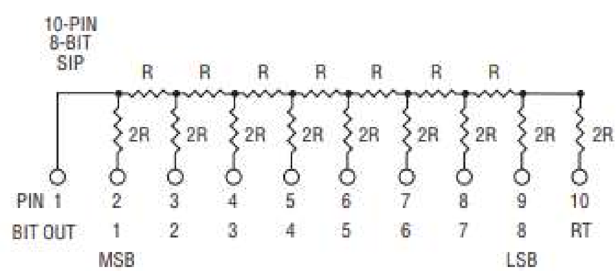


Figure 13. Pinout diagram of DAC (4610X-R2R-103LF)

Figure 24. Pin Configuration of UA741 Op-Amp

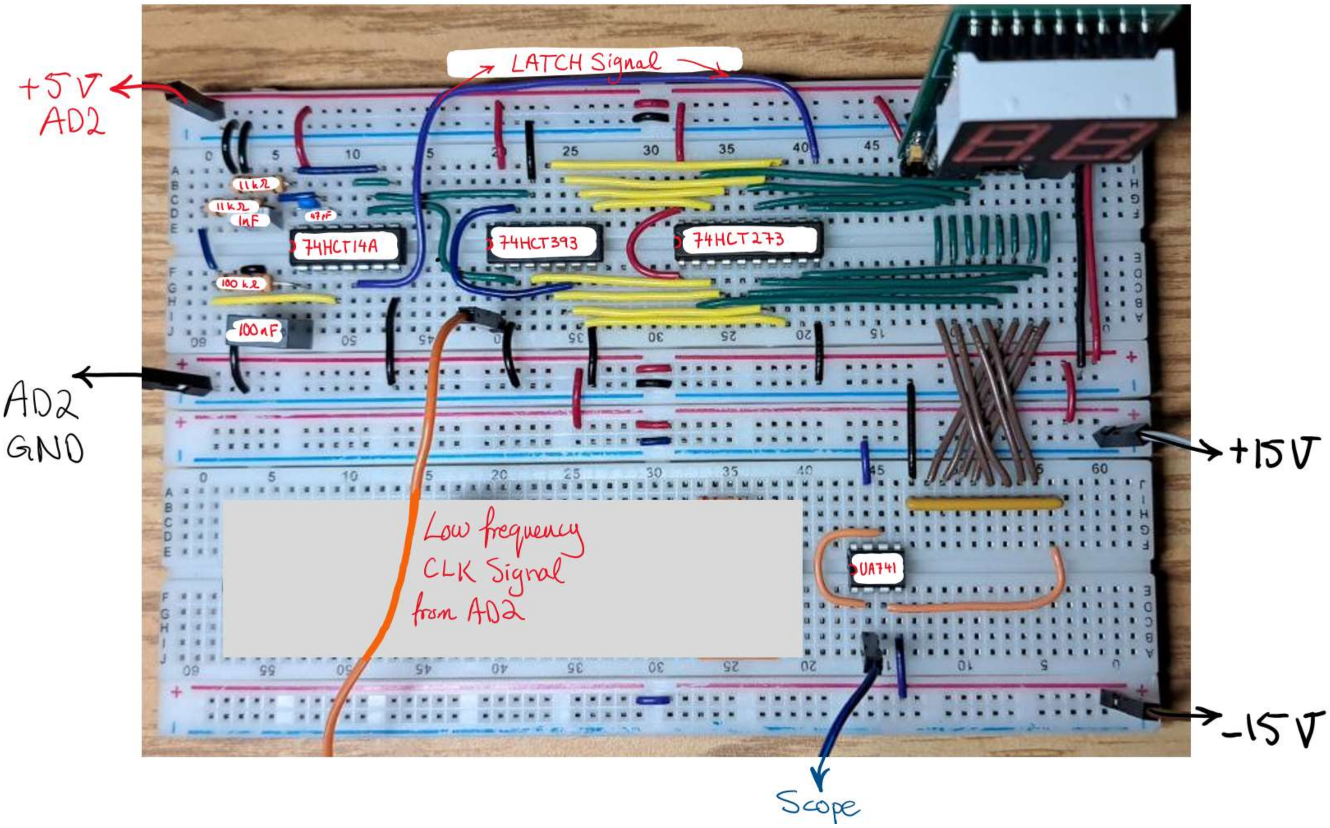


Figure 25. The Counter, D-Latch and DAC constructed on breadboard

To test our circuit, we input a higher frequency CLK signal to the Counter and with the scope, trace the output of the Op-Amp in Figure 26.

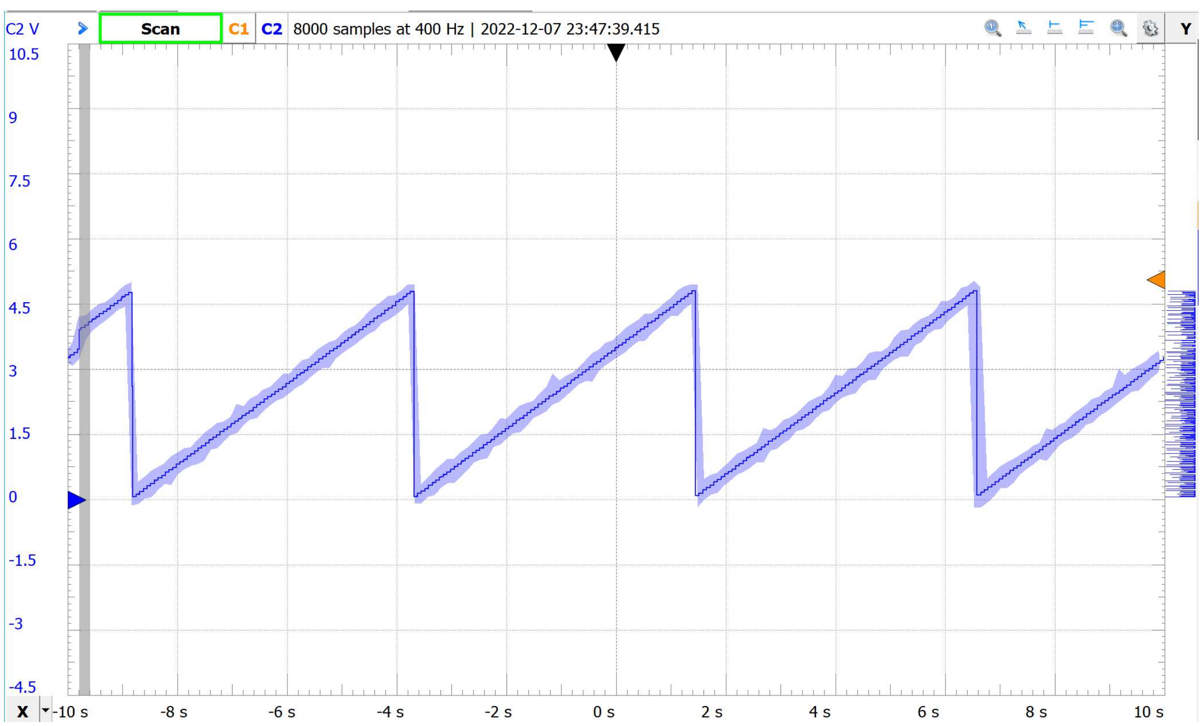


Figure 26. Analog output of the DAC after the Buffer

As expected, the output of the DAC increases with the count number stored by the D-Latch. We can observe this in Figure 26 where the ouput of the DAC is measured and it increases incrementally from 0 V to 5 V which corresponds to our maximum decimal value 255 and drops back to 0 V.

The Op-Amp here functions as a buffer and is necessary for making sure that our Speed Measurement signal is always reflective of the number of rotations counted by the counter, irrespective of the ressistive loads after the DAC.

Troubleshootings in 4.3

Problem: In section 4.3.1, when testing our counter and D-Latch, the count reading on the 7-segment display was always very unstable. Although it would increment correctly, other segments of the display that did not correspont to a specific digit would flicker as well.

Troubleshooting Steps:

- My first assumption was that the wirings were loose, so I spent a good 10 mins rewiring all the green wires to the display seen in Figure 27. Although it made the circuit neater, it did not reslove the issue.
- As expected from any novice student, my next assumption was that the display was broken, so I also switched the display with a few other people. Of course, that didn't work either.
- While this should have been my first step, it was regrettibly my last: I went back to the circuit diagram and took a detailed and closer look at every single connection in my circuit and discovered, I had forgot to connect the CLR of the Octal D-Latch to the 5 V source, and the Latch kept clearing which caused the flickers in the display.

Problem: After stablizing the counter, although I was seeing the counts being outputted, the output from the DAC was not as expected like a sawtooth wave, rather it kept starting from a different voltage than 0V and reseted before it reached 5V.

Troubleshooting Steps:

- Learning from the journey troubleshooting the previous problem, I went throgh the connections laid out in the circuit schematic in Figure 16 after the D-Latch and found that while I had wired the 7-segment display with the correct bits on the D-Latch, I had wired the DAC wrongly in parallell to the display. I later learned that many had a similar problem but they had wired the DAC correctly and the wrong bit wiring on the display was less significant.

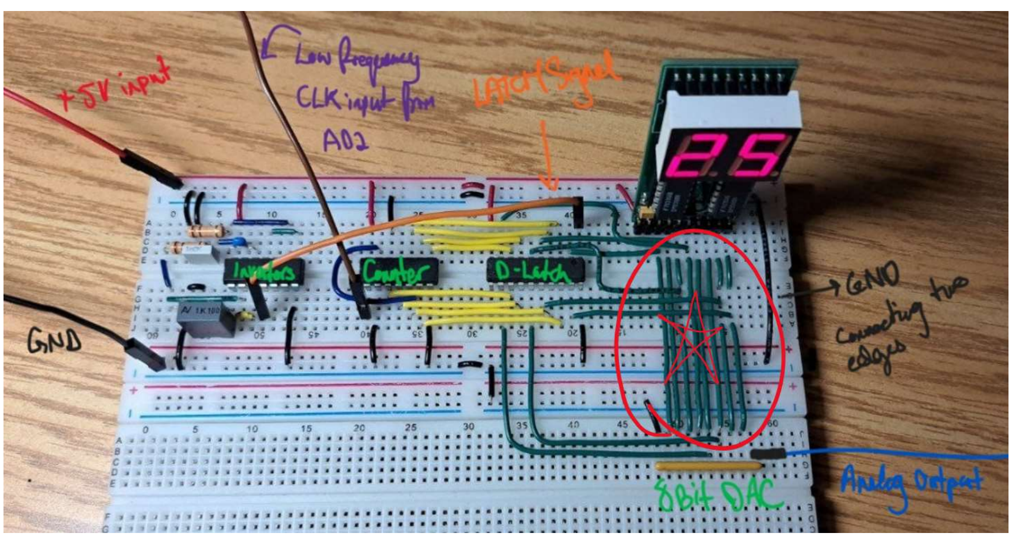


Figure 27. Wiring Problem 4

4.4 Motor Senror and Motor Drive

4.4.0 Circuit Diagrams and Constructions

In the next phase of completing our motor control circuit, we will be wiring the motor sensors, which include a phototransistor and the emittor, the motor driver, the error signal amplifier, and the protecting buffer based on the circuit diagram in Figure 28 below. We will be using the same Op-Amp used in section 4.3.2, the UA 741 chip, with pinout configuration shown in Figure 24. This section of the circuit utilizes a Bi-polar Transistor which will be explained in section 4.4.1.

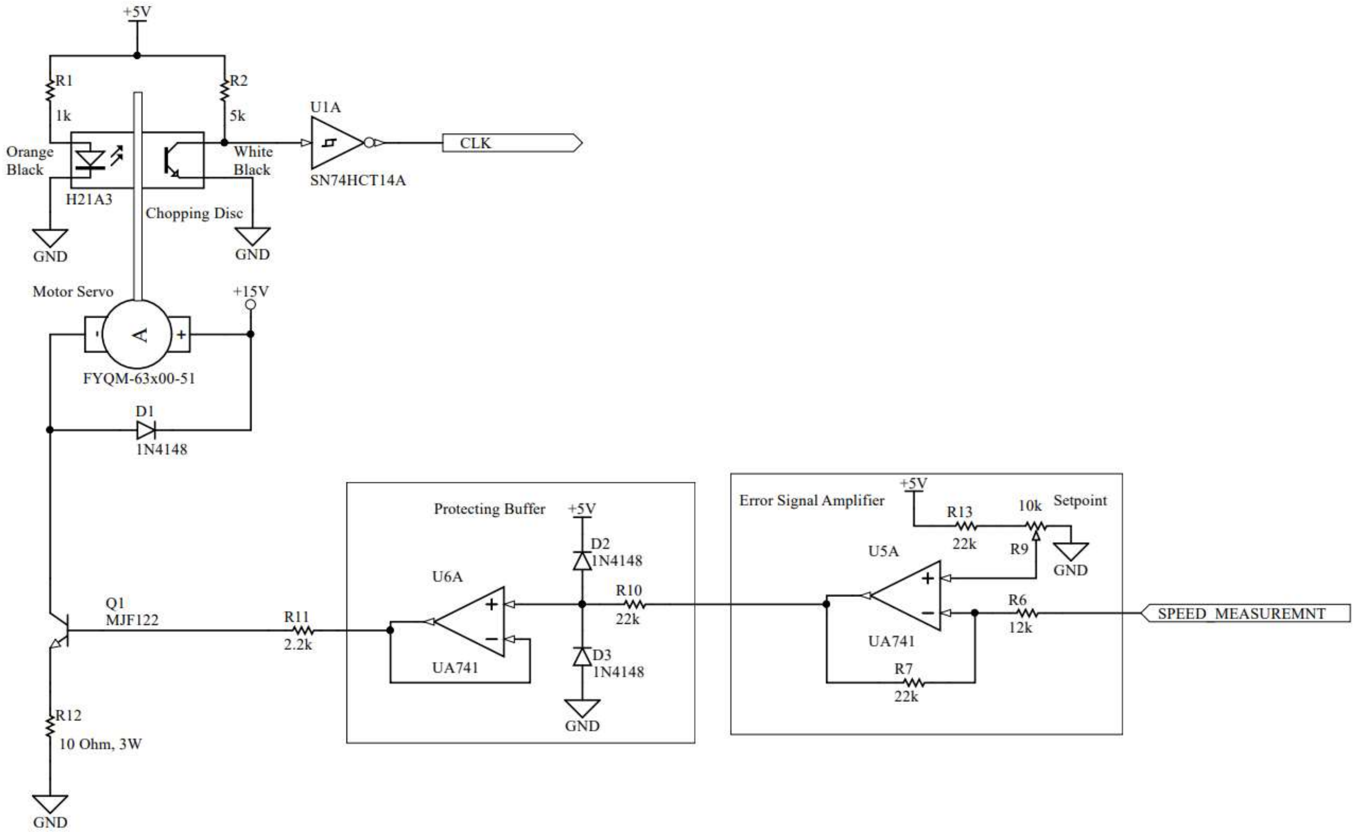


Figure 28. Circuit schematic for the motor sensor and drive and the error signal amplifier.

Figur 29 shows the circuit in Figure 28 on the breadboard along with the previous sections.

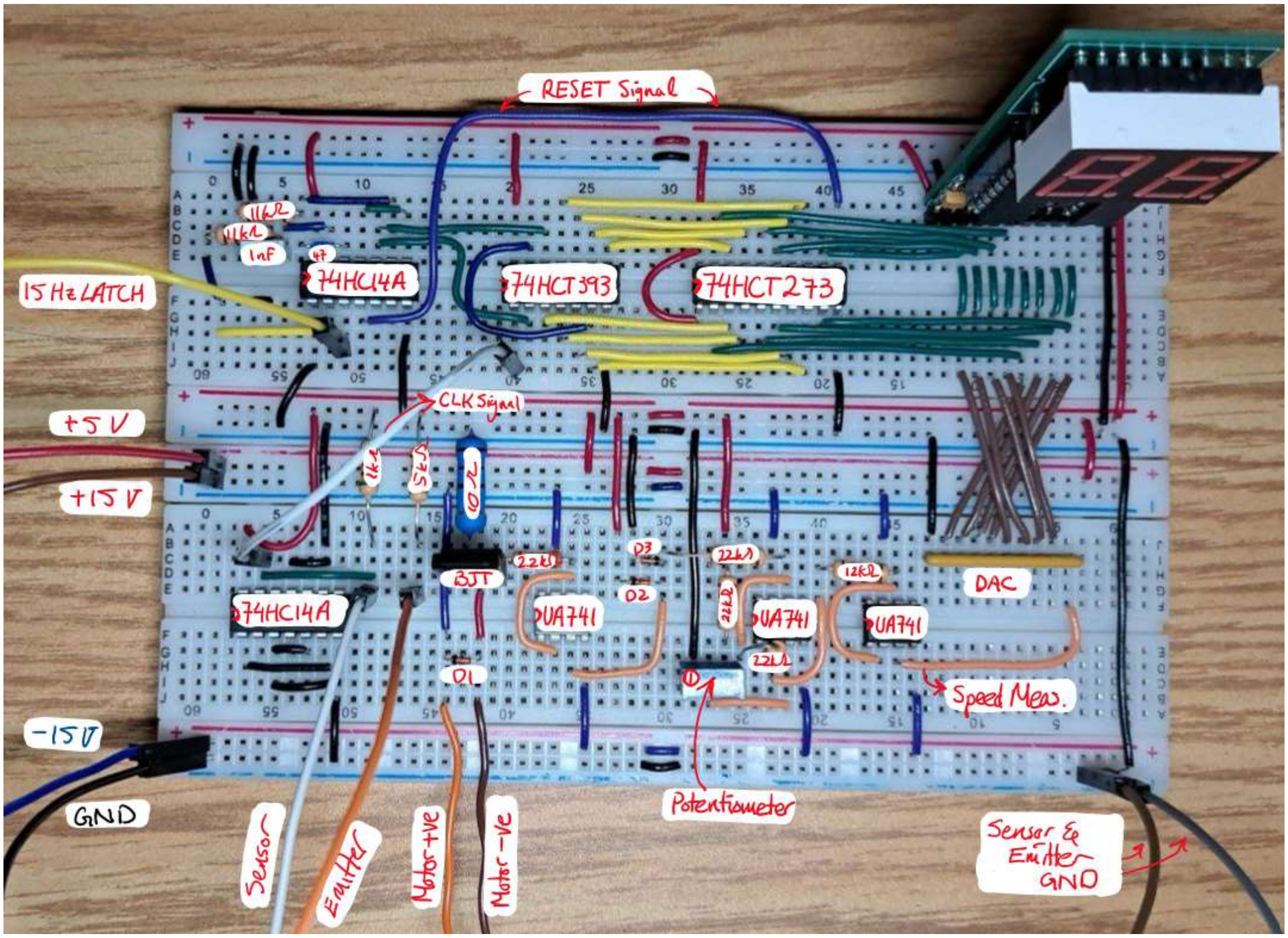


Figure 29. Completed working circuit on Breadboard

4.4.1 BJT Background

Bi-Polar Junction Transistors (BJT) are a type of transistors which allow a small current flow to one of its terminals to controll a lare amount of current flow between the two other terminals. BJTs are of two types, pnp and npn, but we will only look at the npn BJT wich is used in our circuit. An npn BJT has three terminals as shown in Figure 30 which are Emitter (E), Collector (C), and Base (B). The collector has a higher voltage to the emitter and the current from the collector terminal is a multiple of the current of the base terminal with the relationship given as follows:

$I_C = \beta I_B$ with β depending on the particular type of BJT

4.4.2 Motor Sensor and Control with BJT

To integrate our motor control unit in our circuit, we have to make sure that the phototransistor (our motor sensor) which generates a voltage when exposed to light, is working. To test the sensor, we can manually rotate the disc and trace the output of the sensor through scope by probing the connection as shown in Figure 31.

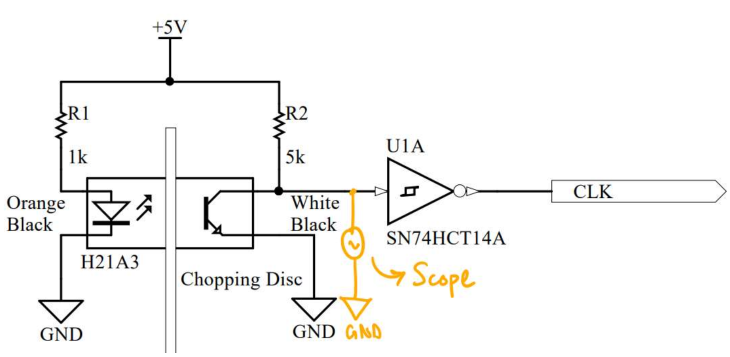


Figure 31. Scope placement to trace the output of the sensor.

Manually rotating the disk means that there are just a few momentarily rotations in the disk and which means only a few pulses during a short time which is very hard to capture on the scope. Instead, we connected the motor directly to the 5 V supply, so the motor will turn continiously with. In Figure 32, we can observe the pulses from the sensor, and confirm the sensor has been wired correctly and works properly.

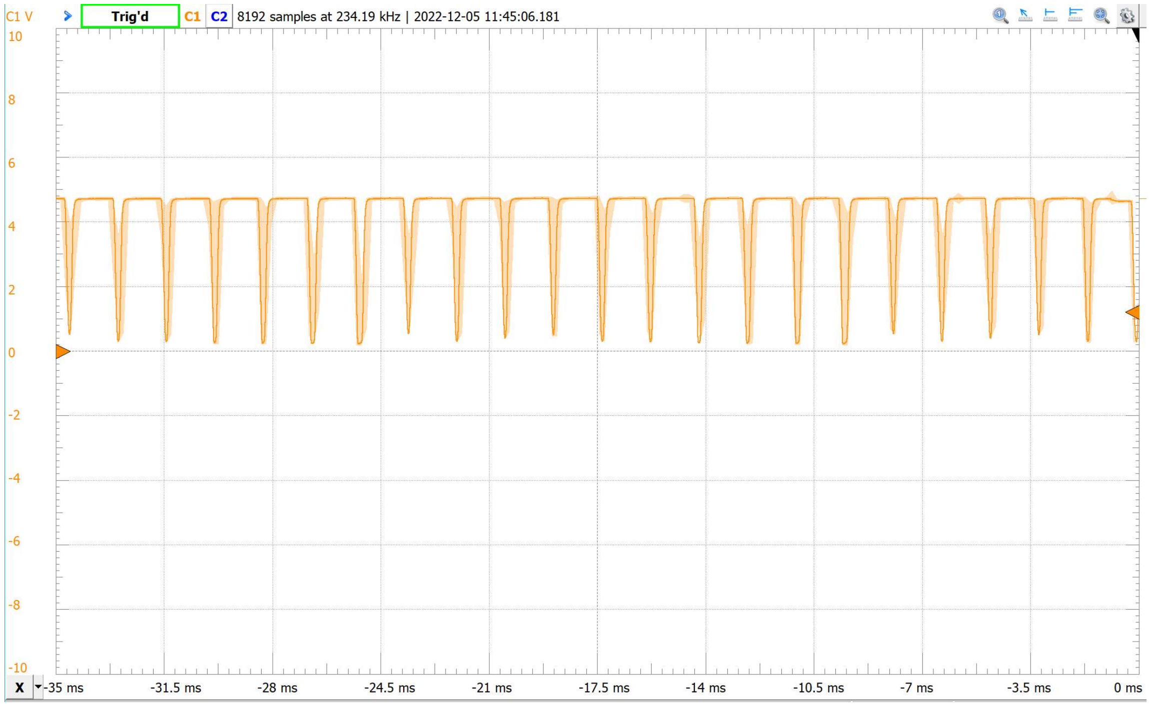


Figure 32. Pulses generated by rotating the motor

We can next connect the scope after the invertor as in Figure 33 to trace the CLK pulse generated by the sensor due to the motors rotation, Figure 34.

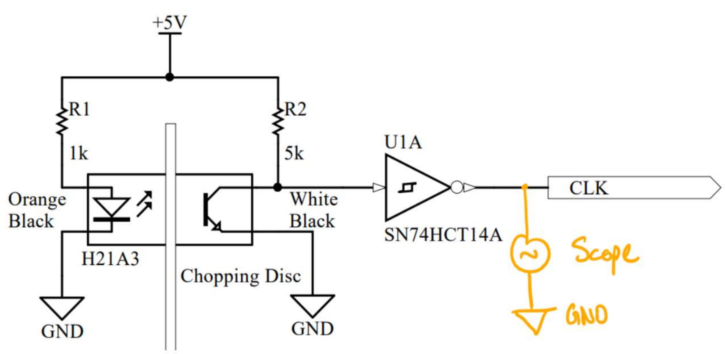


Figure 33. Scope placement to trace the CLK signal

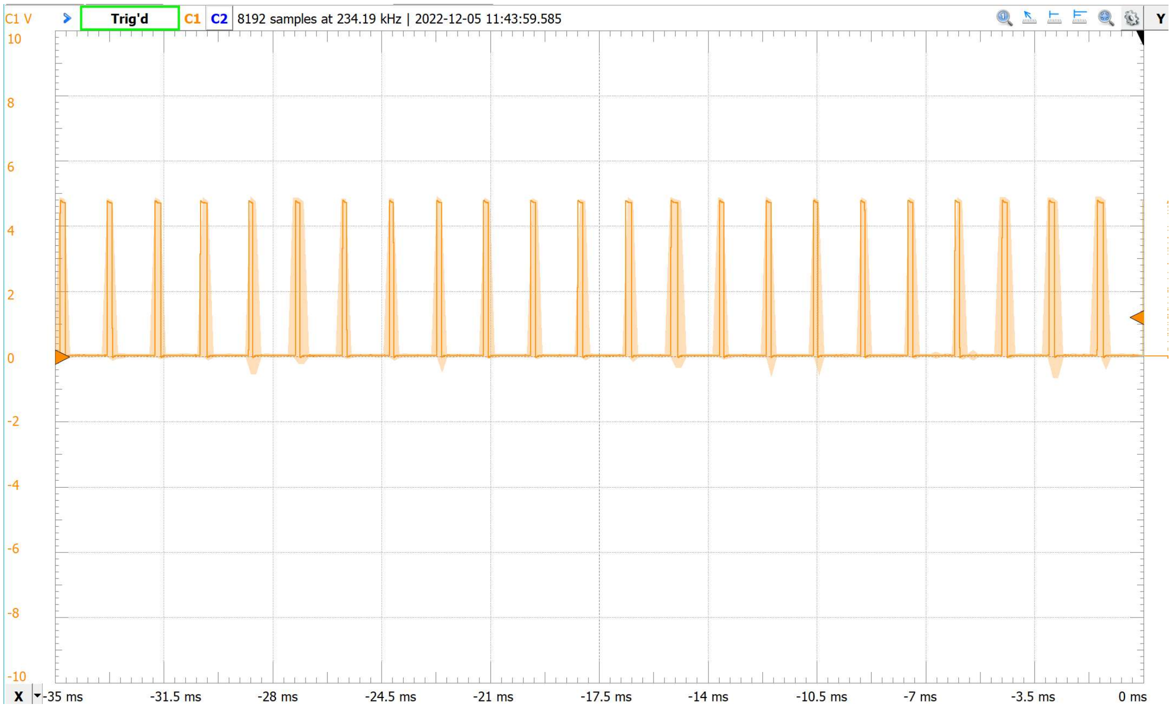


Figure 34. CLK signal as generated by the motor sensor.

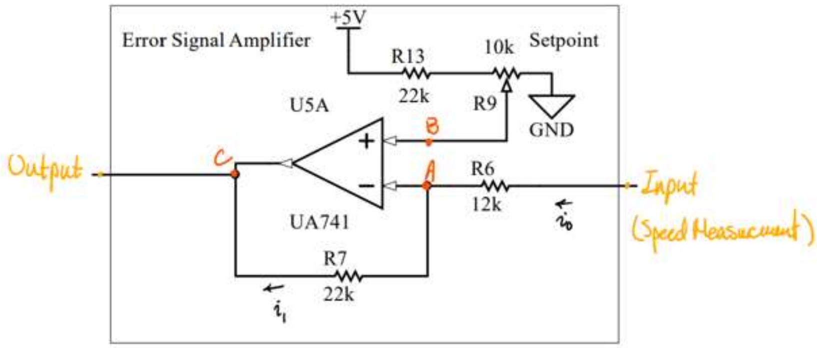
We next connect the CLK signal which we've confirmed is generated to the Counter (74HC393) and ground the motor and the RESETs of the counter. We see that the 7 segment display updates the count every time the wholes in the disk passes over the sensor when we manually rotate the disk. When we enable the RESET and turn the motor. The diode D1 in Figure 28 prevents any current going through the motor in the other way.

The npn BJT acts as a current multiplier in our circuit and controls the current to the motor. Such use of BJT is seen often in control feedback loops because often the device the circuit is trying to control may need to run on higher current while there is no need to run the control circuit with higher currents. So, to minimize power losses, we operate the control unit of the circuit on lower currents and the BJT allows us to then increase the low control current proportionally to a higher current that the our device, the motor in our case, will operate on.

4.5 Error Signal Amplifier and Protecting Buffer

4.5.1 Error Signal Amplifier

Lastly, we go over the error signal amplifier and the protecting buffer. The error signal amplifer in our circuit in Figure 28 is a differential amplifier that scales the difference in the voltage of the Speed Measurement Signal and the input or Setpoint signal that comes from the potentiometer. In Figure 35, we calculate the scale and how the output of the Error Signal Amplifier is determined.



$$V_A = V_B \quad i_0 = i_1 \quad \frac{V_A - V_C}{R7} = \frac{V_{in} - V_A}{R6}$$

$$\rightarrow \quad V_A R6 - V_C R6 = V_{in} R7 - V_A R7$$

$$V_A (R6 + R7) - V_{in} R7 = V_C R6$$

$$V_B = V_{setpoint} \qquad V_C = V_{output}$$

$$V_{out} = V_{setpoint} \left(\frac{R6 + R7}{R6} \right) - V_{in} \left(\frac{R7}{R6} \right)$$

$$V_{out} = V_{setpoint} \left(\frac{32}{12} \right) - V_{in} \left(\frac{22}{12} \right)$$

Figure 35. Relationship between inputs and output of the Error Signal Amplifier module

From the final equation in Figure 35, we can see that the error signal amplifier module scales the difference in the setpoint voltage delivered by the potentiometer which corresponds to our desired motor speed, and the actual motor speed delivered by the speed measurement signal, and outputs this difference. To understant how this output comes into play in controlling the motor speed, lets consider the following scenario:

- Assume we varry the potentiometer to achieve a voltage out of it equivelant to X volts which corresponds to a desired motor speed of Y RPMs
- Lets say the current speed of the motor is less than Y rpms and therfore, the current speed measurement signal is less than X volts.
- Now, since we have a current motor speed less than the desired speed, we would want to speed up the motor which is only achieved by sending more current through the motor.
- As described in Figure 35, the error signal amplifier outputs the difference in our desired signal, V_{setpoint}, and the speed measurement signal, V_{in}, with some factor. Since this difference is positive, the module is outputting a positive voltage.
- This makes sence because we want more current to the motor.
- The reverse is true if the current speed of the motor was higher than the desired speed, and the signal amplifier module would output a negative voltage.

4.5.2 Protecting Buffer

As we just explained, the error amplifier would output a positive voltage if we need to increase the speed of the motor and a negative voltage when we need to decrease the speed of the motor. However, this can be problematic as we wouldn't want to suddenly rotate the motor in reverse. So, the protecting buffer is placed to protect the BJT and the the motor from a negative voltage and reverse current or a too high voltage.

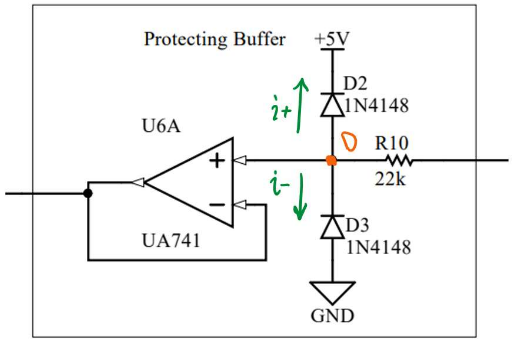


Figure 36. The Protecting Buffer

This two diodes D2 and D3 in Figure 28 play the role of protectors. Since the diodes only allow current to flow only in one direction, we can ignore them when the voltage at point D is between 0 and 5 Volts. But when the voltage is above 5 Volts, the upper diode acts as a wire and the caps the utput voltage at D to 5 Volts. When the voltage at D is negatvie, the lower diode, D3, acts as a wire and grounds D, resulting in a 0 Volts output. This way, when the the motor speed is higher than the setpoint, the motor is slowed down simply by not providing any power to it until it reaches the desired speed instead of reversing the rotation and "breaking"

Troubleshootings in 4.5

Problem: Before connecting the motor and the error amplifier, my LATCH signal was working perfectly, but now it was distorted and somtimes it even disappeared.

Troubleshooting Steps:

- I first though I had misplaced something in my Pulse generator, so I took a look again, but every component was in its right position.
- I learned from my TA that the LATCH signal can sometime behave unexpectedly, and so I can input a 15 Hz square wave with a 2.5 V amplitude and 2.5 V offset with the Wavegen. This resolved the issue and I grounded the first inverter.

5. Conclusion

After a month of work on this circuit, we finally conclude with a working circuit and the TAs test of pulling a wire.

In Figure 37. we can see the ccompleted motor control circuit working. The figure is not annotated as it is the exact circuit as in Figure 29 which was annotated and is more clear.

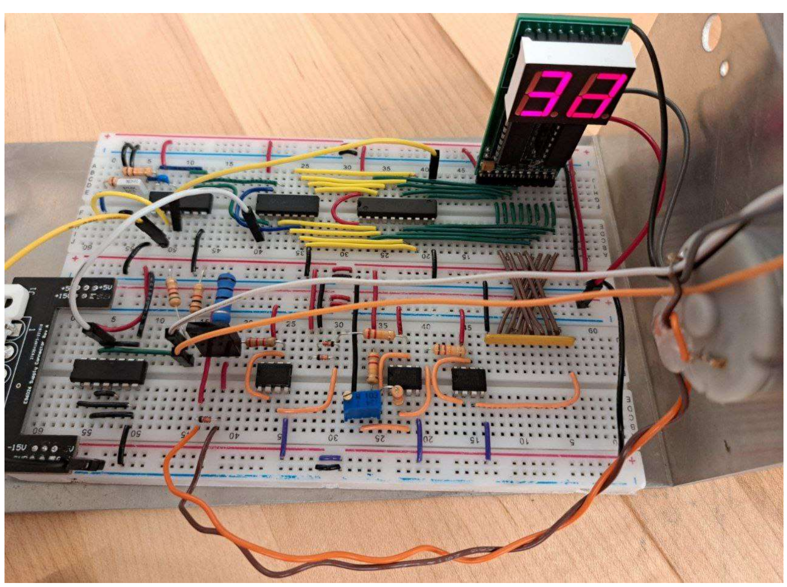


Figure 37. Completed circuit at work

With a working circuit, we can now measure the speed of the motor with different setpoint voltages. To measure the setpoint voltage, we probe with the scope the output of the potentiometer as shown in Figure 38, and use the average measurement function of the scope.

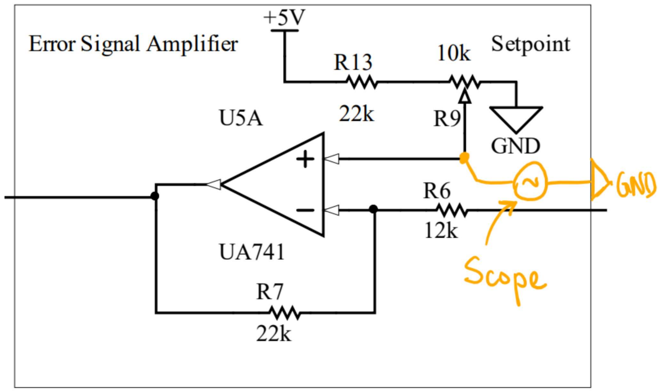


Figure 38. Scope placement for reading setpoint voltage

To mesure the speed of the motor, we can use our circuits own display; however, we have to be cognizant of what the display is actually showing. The display is showing the number of CLK pulses that the motor sensor generates between each RESET pulse. The RESET pulses are generated at a frequency of 15 Hz, meaning there is a pulse every 1/15th of a second. So, the display desplays the number of CLK pulses in 0.067 seconds. Now we have to find the relationship between the CLK pulses and the rotation of the motor. The motor disk contains 10 holes and the sensor pulses every time the holes pass over the sensor which means 10 CLK pulses per rotation. Putting together these two relationships, we derive the following equation:

$$\text{Motor RPM} = \text{Display Count (CLK)} * 15\text{ Hz } * \left(\frac{1\text{ Rotation}}{10\text{ CLK}}\right) * \left(\frac{60\text{ sec}}{1\text{ min}}\right) = \text{Display} * 15 * 6$$

We also have to take into account that the display shows the count in hexadecimal and we have to convert that to decimal.

With the above formula, we get Table 1 below which shows the motor speeds at different setpoint voltages.

```
Voltage = [0.38;0.61;0.63;0.78;0.95;1.11;1.29;1.48;1.53];
Display = ["00";"00";"01";"0E";"1A";27;34;"3C";"3F"];
Decimal = [0;0;1;14;26;39;52;60;63];
RPM = Decimal*15*60/10;
Speed_Hz = RPM/60;
t = table(Voltage,Display,Decimal,RPM,Speed_Hz)
```

t = 9×5 table

	Voltage	Display	Decimal	RPM	Speed_Hz
1	0.3800	"00"	0	0	0
2	0.6100	"00"	0	0	0
3	0.6300	"01"	1	90	1.5000
4	0.7800	"0E"	14	1260	21
5	0.9500	"1A"	26	2340	39
6	1.1100	"27"	39	3510	58.5000
7	1.2900	"34"	52	4680	78
8	1.4800	"3C"	60	5400	90
9	1.5300	"3F"	63	5670	94.5000

Table 1. Speed and RPM measurements

To make our display directly show the speed of the motor in RPM, in hexadecimal, we can change the frequency of our LATCH signal to make the equation we derived equal to the display count, which means the LATCH signal to be at 1/6 or 0.167 Hz. If we are using the Wavegen, we can simply set this frequency, but if we are using the Pulse generator circuit, we can choose a capacitor and resistor combination that generates a square wave with this frequency. We should note that our RPM values with higher voltages are well above the 1000 mark which would require a 16-bit counter and D-Latch and a 4 digit display, which are possible, but another way would be to generate a 10 Hz LATCH signal and display the motor speed in Hz or revolutions per second, which is possible with our current components.

The maximum speed my motor ran for and the display showed a stable reading for was 3F on display which corresponds to 5670 RPM and a maximum voltage of around 1.53 V out of the potentiometer. We can increase this speed by setting a higher voltage as the setpoint which could be achieve by replacing the resistor before the potentiometer, R13 in Figure 28, with a smaller resistance.

Through this twenty hour labratory experiment, we learned about multiple circuit components and how they function in our journey to construct the motor control circuit.

We learned about hysteresis in Schmidt-trigger Inverters which are capable of iverting a Digital signal at different thresholds based on the previous state, or history, of the signal. Using the scope, we found the thresholds to be 1.82 V when the signal is going from High to Low and 2.64 V when the signal is going from Low to High. We observed the behaviour of RC coupled circuits and their ability to produce square wave signals and delays when coupled together, and we calculated the theoretical and experimental values of their time constants. We learned that a counter counts the number of CLK signals and the D-Latch stores the count in bits by latching on to the state of the bit until the previous bit goes from High to Low, or 1 to 0. WE observed the DAC converting the digital signal to an analog signal, and realized the significance of buffers or Op-Amps in ensuring that our analog signal is maintained despite the load after the signal. We learned how a differential amplifier is used to amplify the error between our current signal and a desired signal and calculated the scale of the difference amplifier theoretically. We used diodes to cap a signal between two voltages, 0 and 5 Volts. And finally, we learned that BJT can allow us to control a relatively larg current flow with a very small amount of current, and how that is useful in control circuits becaues it minimizes power losses within the control circuit while running the device we want with higher power. We have further explained the function and reason for each component and section of the circuit in more detail in the corresponding section of the lab report.