MECH 368

Group Project

P-28

Stepper Motor Speed and Direction Control without Controller

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Introduction

The goal of this project is to familiarise the user with sequential and combinational circuit design. This project also provides the maker with a chance to explore in depth the working and control of a stepper motor.

The most important requirement of this project is to control the speed and direction of a stepper (28BYJ48) using the joystick in the Arduino kit and without using a dedicated controller i.e. requires the design of a pulse generator and a direction switching module.

Pre-requisite Information / Theory

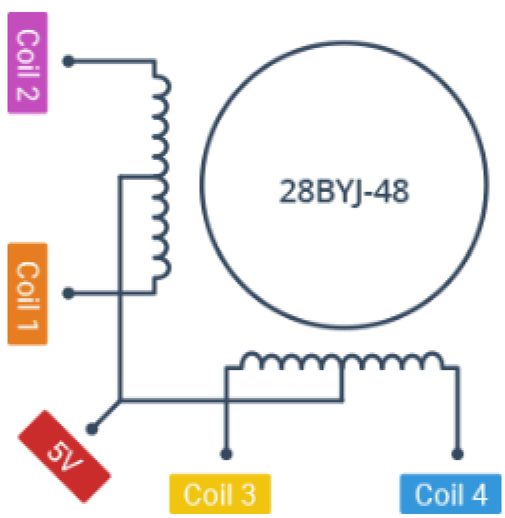


Figure 1: 28BYJ48 Input Wires

Each of the wires connected to the stepper represents a coil, the red wire is common to all the coils and is pulled high. When one of the other leads is pulled low, a coil is said to be energised and stepper rotates. The stepper rotates for specific coil energization / pulses and these are refereed to as step sequences.[1]

Important intuition: [1]

- The sequence of pulses determines the spinning direction of the motor.
- The frequency of the pulses determines the speed of the motor.
- The number of pulses determines how far the motor will turn.

Usually a microcontroller like an Arduino is used to feed these control pulses into the ULN2003 driver board, in this project we will not use an Arduino and instead use sequential and combinational circuits to control the stepper.

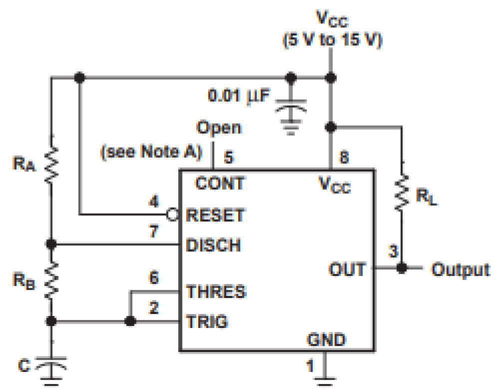
From the AccelStepper Arduino library and this YouTube video [2], the step sequence for the most simple full-step driving of 28BYJ48 is

	Pulse / Step 1	Pulse / Step 2	Pulse / Step 3	Pulse / Step 4
Input 1 (Blue)	1	1	0	0
Input 2 (Pink)	0	1	1	0
Input 3 (Yellow)	0	0	1	1
Input 4 (Orange)	1	0	0	1

Figure 2: Required Sequence for Full-Step control of 28BYJ48

From this required sequence, if each step is the next clock cycle, we input a low signal for 2 clock cycles and a high input for 2 clock cycles looped infinitely to drive the motor in one direction i.e. from input 1-4. For full-step driving in the reversed direction the pulses are applied in the reverse order i.e. from input 4-1.

The frequency of NE555 is controlled by the value of R1, R2 and C connected to the clock w.r.t. the figure below:[3]



Pin numbers shown are for the D, JG, P, PS, and PW packages.
NOTE A: Decoupling CONT voltage to ground with a capacitor can improve operation. This should be evaluated for individual applications.

Figure 12. Circuit for Astable Operation

Figure 3: Clock Wiring

The frequency for an astable clock is given by: $\frac{1.44}{(R_A+2R_B)C}$, in our circuit RB will be replaced by the joystick potentiometer.

Such a sequence is using the second bit of an asynchronous binary counter as input to a SIPO shift register. The second bit has half the frequency of the first bit (which follows clock frequency) so the serial output into the shift register would follow the sequence in Figure 2.

The motor cannot be driven by the high logic outputs as the ICs cannot drive sufficient current to support the motor. Hence transistors are required. The ULN2003 driver board has a ULN2003 IC with 7 Darlington transistors and can be used to drive the motor. It also provides easy access to the motor input pins.

The switch on the joystick is debounced using an RC filter and one of the 5k potentiometers is used to control the frequency of the NE555 timer; hence controlling the speed of the stepper.

A switching circuit is designed using a JK flip flop, 2 shift registers (SR1 and SR2) and an XOR logic gate, the shift registers have enable pins that must be held at a high signal to allow the register to read serial input and we utilise this feature to enable reversing of directions. The flip-flop is used as a T flip flop that is toggled by the joystick switch and at each toggle it switches between enabling one of the 2 shift registers i.e. at one time one of the shift registers provides the required pulses while the other has low-level signal at all its outputs. The shift registers are wired into the XOR gate such that the 1st input from SR1 is compared with the 4th input from SR2, the 2nd input from SR1 is compared with 3rd input from SR2 and so on. An OR gate could have also been used to provide the needed output.

A (SR1)	B (SR2)	Y
1	0	1
0	0	0
0	0	0
1	0	1

Figure 4: Required Logic for Switching

An MB102 power supply is used to power the ICs with 5V and a 12V power supply is used to power the motor driver.

Since our SRs are positive edge triggered and Flip flops are negative edge triggered, we obtain stable data stream such that data is shifted at rising clock edge and flip flops toggle at falling clock edge.

Modules (enclosed in broken line box)

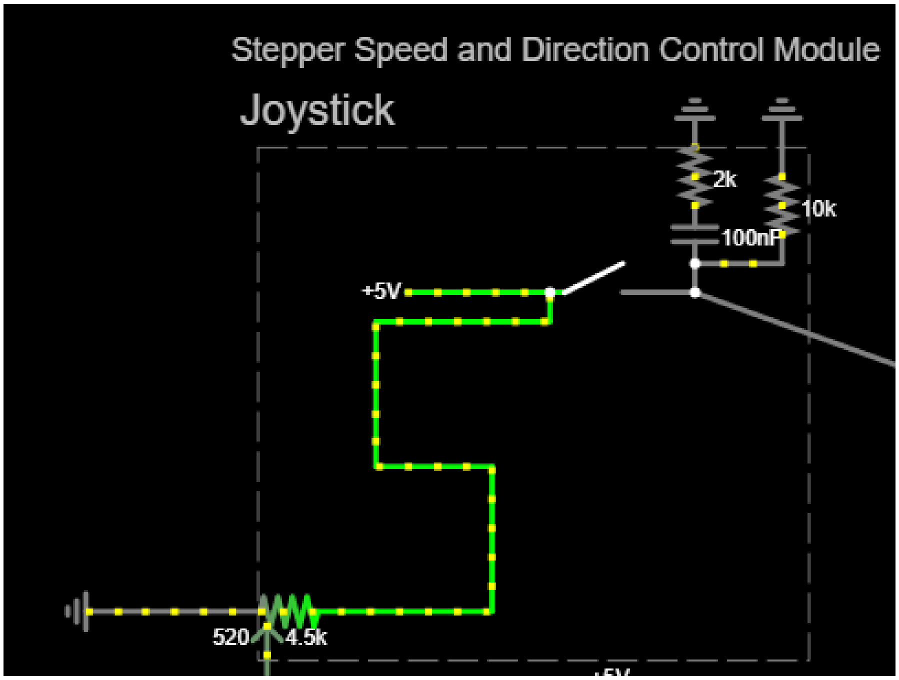


Figure 5: Joystick Module

The above module consists of a potentiometer to vary the frequency of the clock and switch to reverse direction of the stepper. The switch is pulled-down and also debounced using an RC filter.

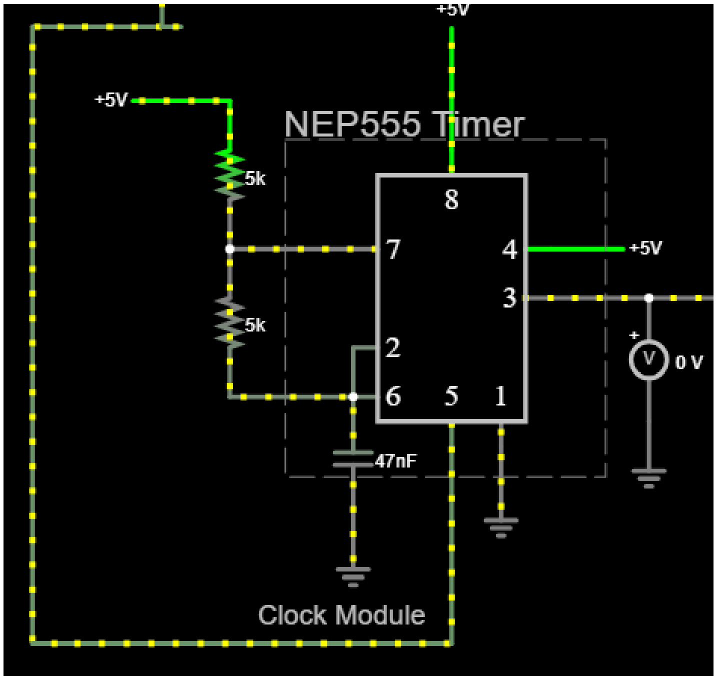


Figure 6: Timing Module

The above module consists of the NE555 IC responsible for synchronising behavior of the circuit and also control the stepper speed.

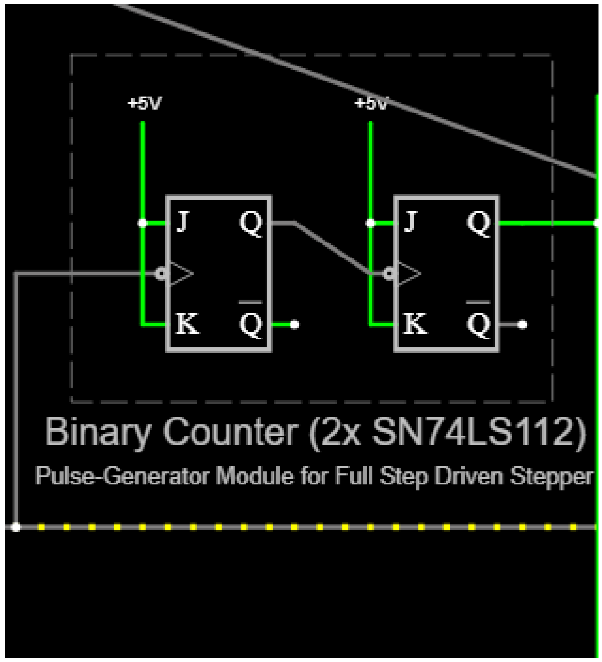


Figure 7: Full-Step Pulse Generator Module

In the above module the full step is generated using a 2 bit binary counter (asynchronous) made up of 2 JK flip flops. The output of the 2nd flip flop is sent as serial input into shift registers. The 74LS112N flip flops are negative edge triggered.

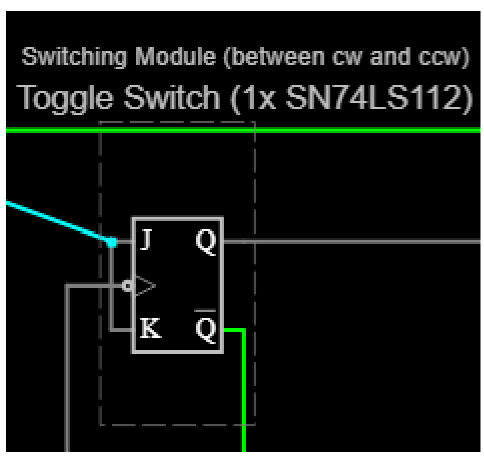


Figure 8: Switching Module

Both the shift registers (SR) have an 'enable' pin that must be set high to read the serial input otherwise all outputs of the SR are low-level signals, the switching module controls the state of this enable pin. The JK flip flop is wired to act as a T flip-flop. Q and Q' control the enable pins of SR1 and SR2 respectively.

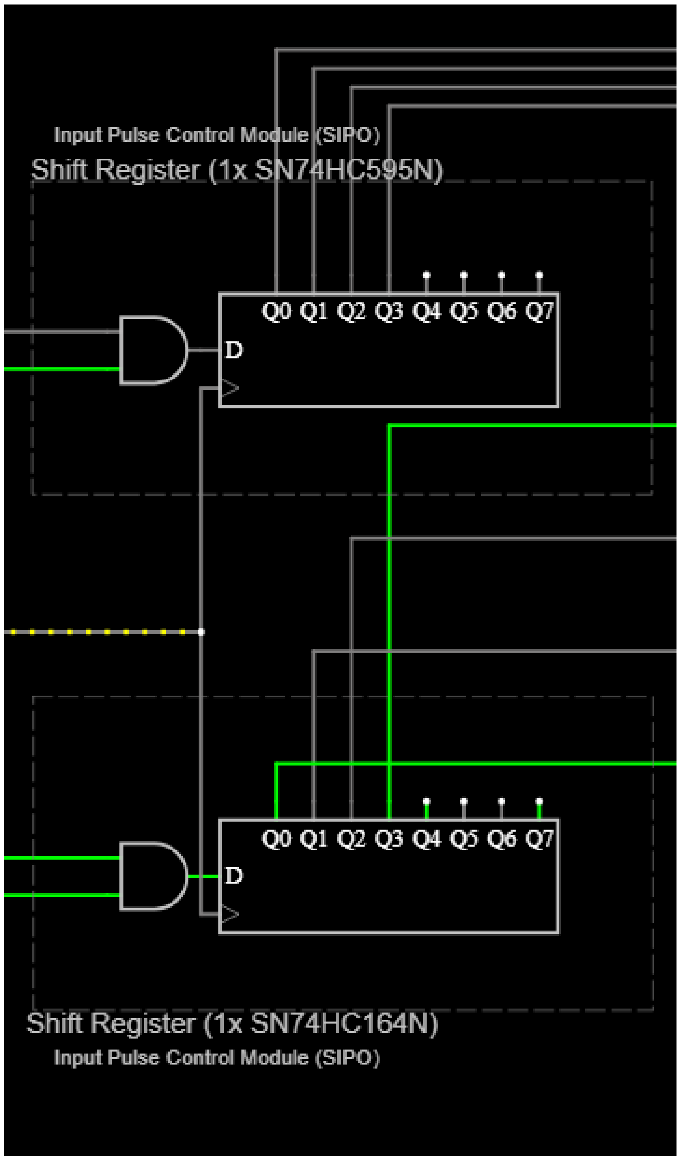


Figure 9: SIPO module

The shift registers are used to convert the serial input from the binary counter into 4 parallel output signals that control the stepper motor. Both the shift registers are positive edge triggered.

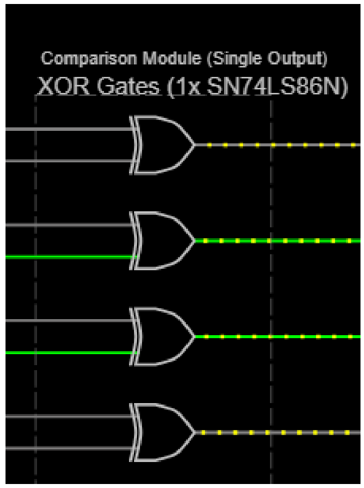


Figure 10: Combination Module (Single Output)

Since the ULN2003 has only 4 accessible input pins, the outputs from the 2 SRs must be combined to control the stepper, as stated in theory an OR / XOR gate can be used as shown in above module. (one of the SR outputs are always low-level)

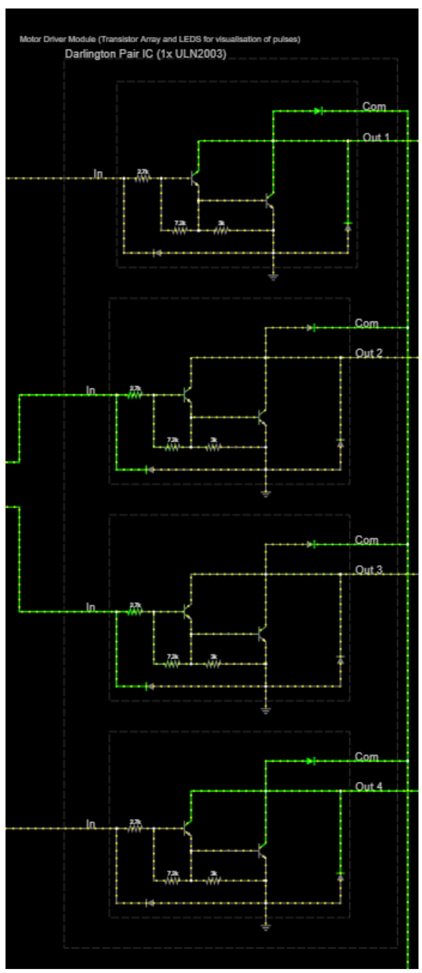


Figure 11: Transistor Driver Module

The ULN2003 driver board has a ULN2003 IC with transistors that provides ample current to be able to drive the motor. The motor cannot be driven by the IC output signals from the XOR gate as the ICs cannot handle current required by the load. This IC has 4 LEDs connected to the output that can help visualise the pulses.

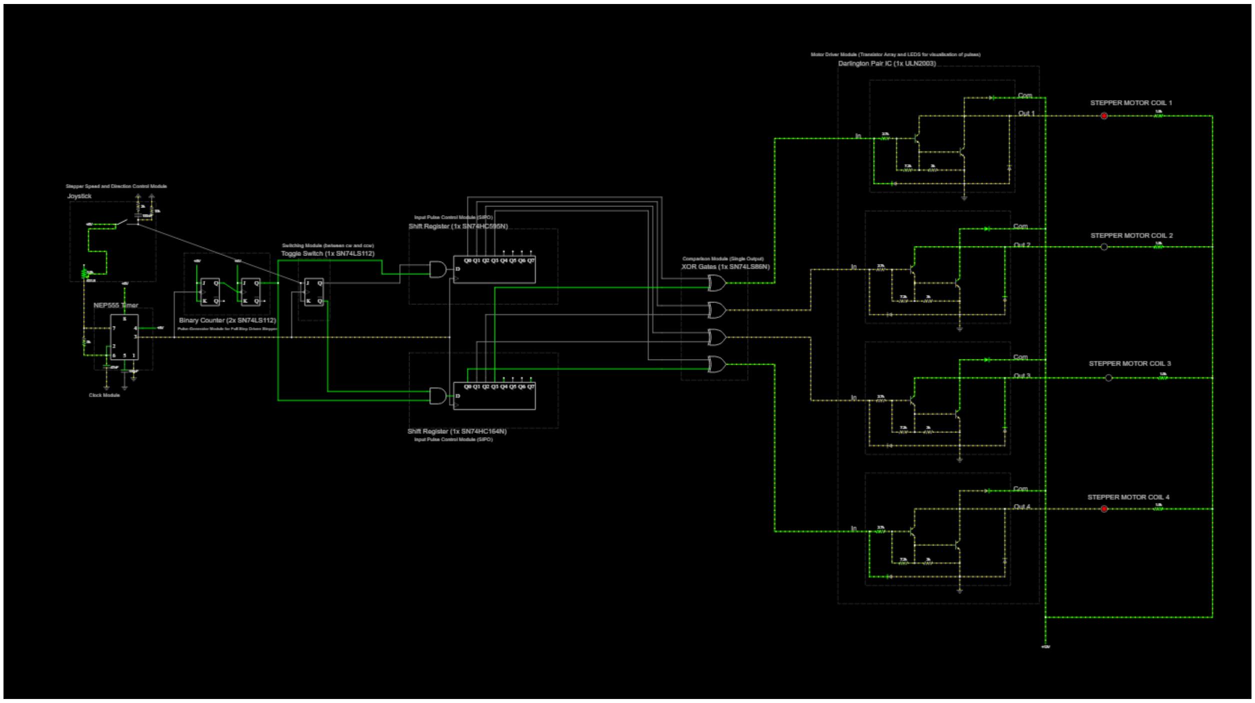


Figure 12: Complete Circuit

Falstad Link (Resistance Control Frequency)

https://tinyurl.com/2ar76zr9

Falstad Link (Voltage Control Frequency)

https://tinyurl.com/26ywf3kr

Deviations / Points to be Noted

- A separate high-frequency clock can be used to drive the switching module in Figure 8 that is toggled by the joystick switch. If we want to drive the stepper at super low speeds i.e. drive the clock at low frequency, the switch needs to be held for a longer time to toggle the flip flop. This separate clock ensures that the switching module reads data at a constant frequency regardless of stepper speed.

- The joystick has a potentiometer range from 0 ohm to 4.4k ohm and around 3.3 ohms at its mid position. This potentiometer is very sensitive and does not linearly slide across its range. For a 2.2 uF capacitor and RA = 5k ohm, this gives us a maximum and minimum frequency of 124.78 Hz and 45.78 Hz. The difference between these 2 values is not super apparent in real life and in simulation. *For greater speed control a 50k to 100k potentiometer is recommended.* **In my experimentation, the motor stalls at frequencies greater than 575Hz, so to have greater speed control within the same frequency range a much larger joystick potentiometer is recommended.**

Weird behavior of joystick potentiometer:

https://youtu.be/P7e5XV3rYuw

The joystick is super sensitive and does not rest at an expected value of 2.5k ohms.

The 28BYJ48 Stepper has a 1:64 reduction, 360 degree rotation consists of 2048 steps. Since we are driving motor at full-step, frequency = no. of steps per second, from this we can obtain estimated time to complete a revolution at a given frequency.

Joystick Center position frequency:

R2 = 3.3k Ohm, R1=5.1k Ohm , C = 2.2 uF

$$\text{Frequency NE555} = \frac{1.4}{(R1+2*R2)C} = 54.4 \text{ Hz}$$

$$\text{Time per Revolution} = \frac{2048}{54.4} = 37.7 \text{ sec}$$

Joystick Pull towards button position frequency:

R2 = 4.4k Ohm, R1=5.1k Ohm , C = 2.2 uF

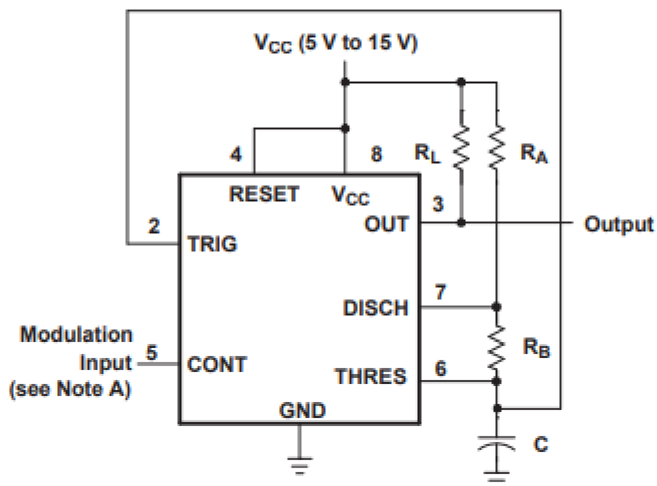
$$\text{Frequency NE555} = \frac{1.4}{(R1+2*R2)C} = 45.8 \text{ Hz}$$

$$\text{Time per Revolution} = \frac{2048}{54.4} = 44.7\text{sec}$$

These calculations serve to show that it is hard to observe the speed change over the joystick potentiometer range with the naked eye.

Solution to the Small Potentiometer Problem:[4]

If instead of grounding pin 5, you connect it to a varying potential since the joystick is configured for varying potential across its range of motion. As this voltage is increased, it decreases the frequency of the output.



Pin numbers shown are for the D, JG, P, PS, and PW packages.

NOTE A: The modulating signal can be direct or capacitively coupled to CONT. For direct coupling, the effects of modulation source voltage and impedance on the bias of the timer should be considered.

Figure 20. Circuit for Pulse-Position Modulation

Figure 13: Circuit for VCO

The output frequency is not formulated in the datasheet, but a relationship can be found empirically.

Simulations

The clock output is obtained from pin 3 of NE555 IC. The Q and Q' values are obtained from pin 5 and 6 of 74LS112N JK flip flop IC used in switching module. The serial input for shift registers SR1 and SR2 is obtained from the 9th pin of the 2nd flip flop of the 74LS112N IC used in the binary counter module. The SR1 outputs are obtained from any 4 consecutive output pins on the SRs, which in my case is pins 1-4 on SR2 (SN74HC595N IC) and pins 4,5,6 and 10 on SR1 (SN74HC164N). The outputs for the XOR gate are obtained from pins 3,6,8 and 11 on the SN74LS86 IC.

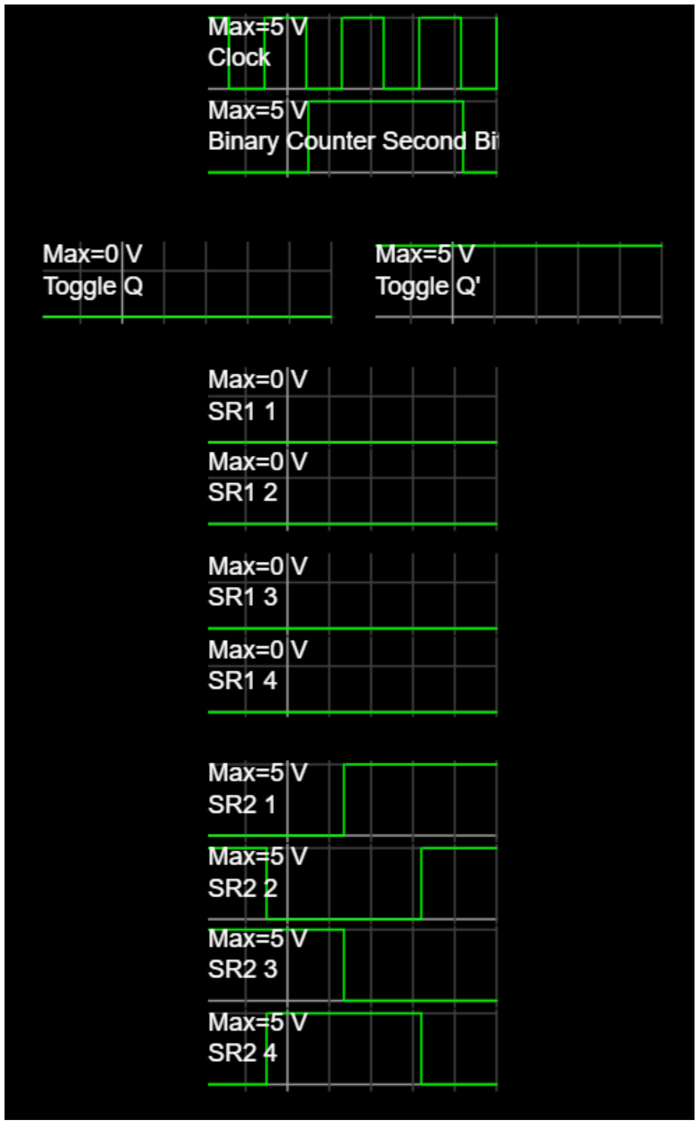


Figure 14: SR behavior when Q=0 and Q' = 1

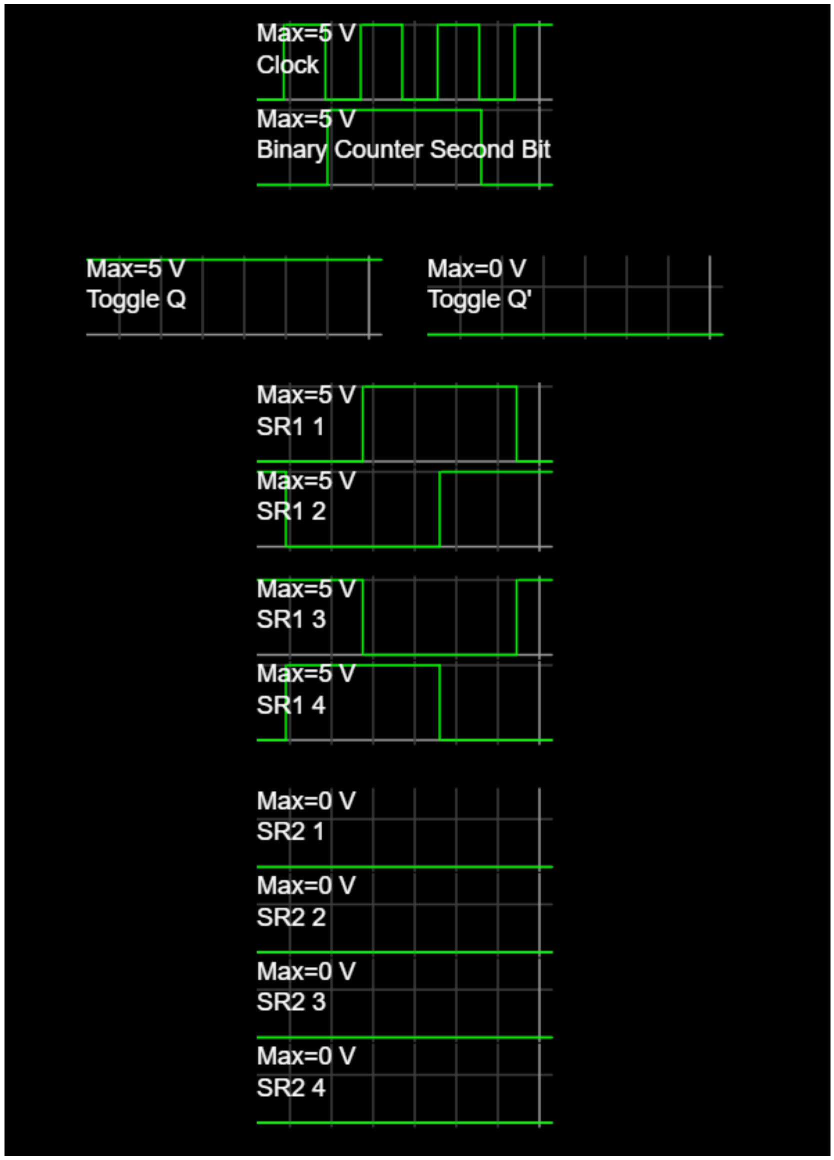


Figure 15: SR behavior when Q=1 and Q'=0

From the first 2 graphs in figure 13 and 14, it is evident that the second bit of the binary counter stays high / low level for 2 rising / falling edges of the clock signal which is exactly what we require for our full step pulses.

From figure 13, when Q'=1 and Q=0, all outputs of SR1 are low and SR2 is fed the serial input from the binary counters second bit whereas the vice versa is true when Q=1 and Q'=0 as seen in figure 14.

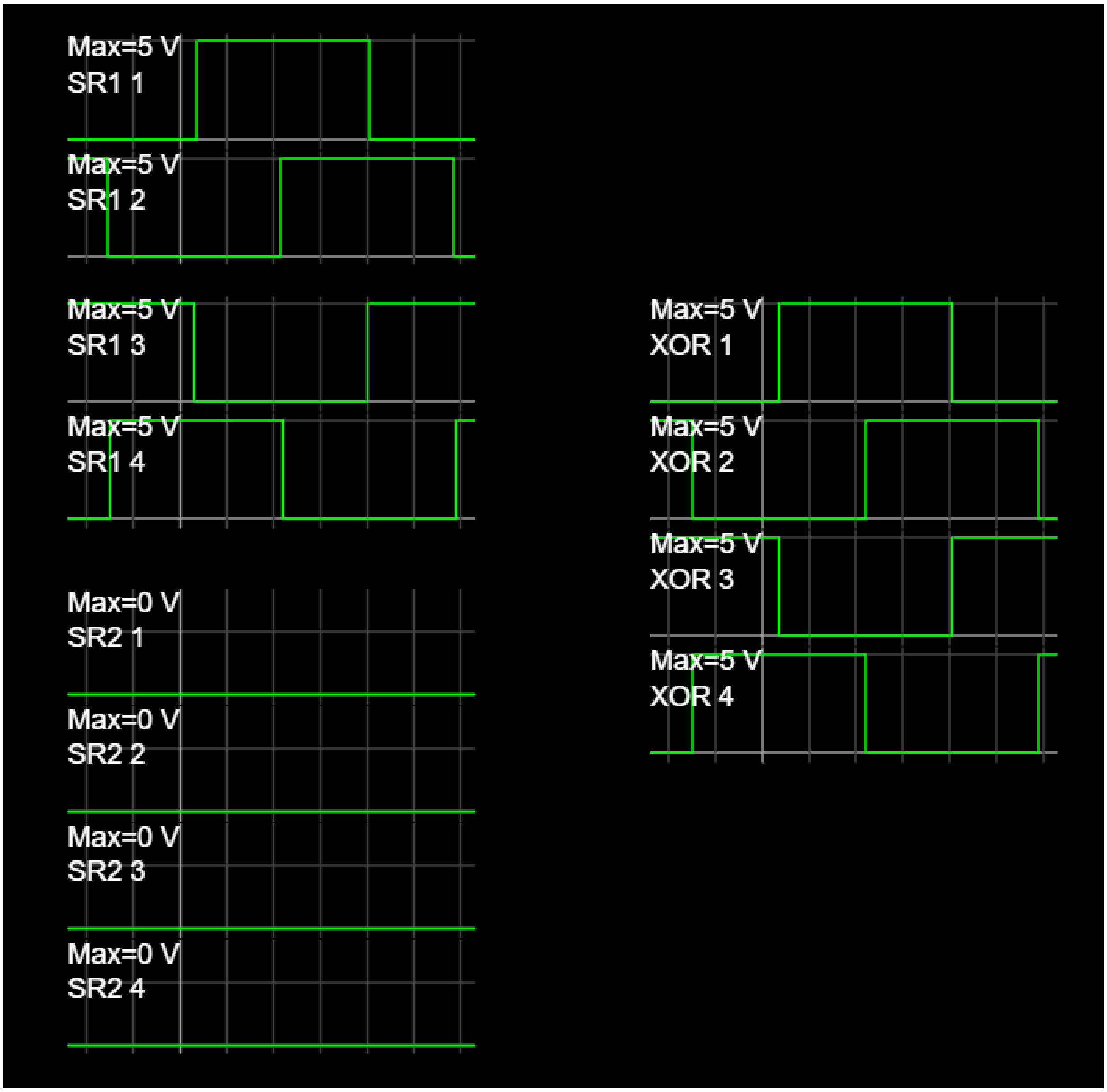


Figure 16: XOR Output

From figure 15, it is clear that the 4 outputs of the XOR gate follows the parallel outputs from the non-low level SR.

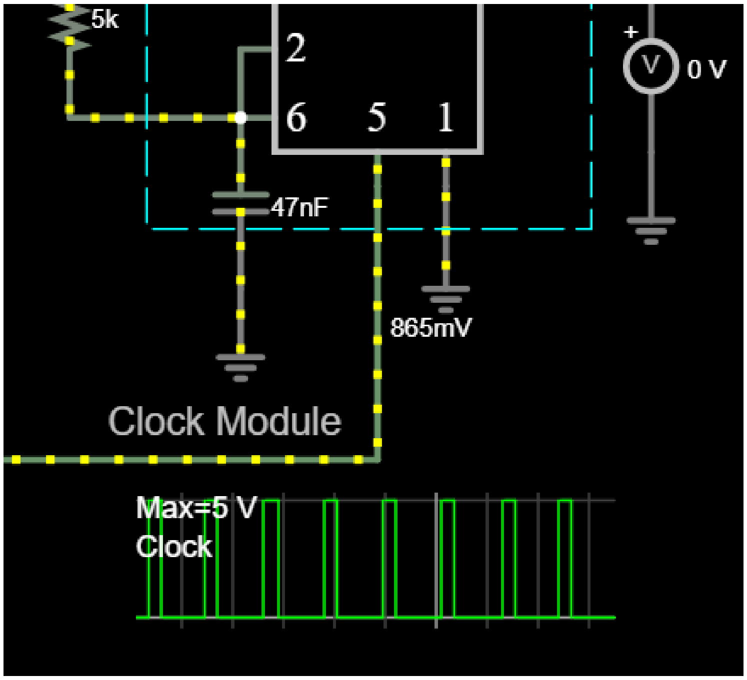


Figure 17: Low Control Voltage = High Frequency

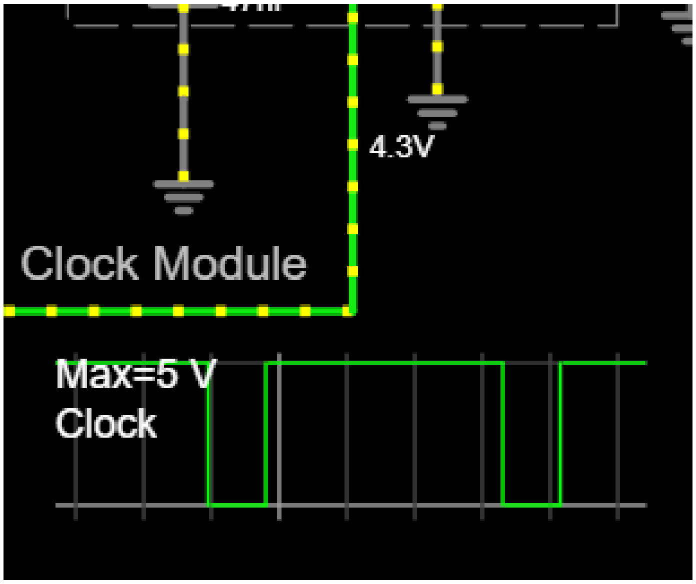


Figure 18: High Control Voltage = Low Frequency

As the voltage across the control (pin 5) input of NE555 is varied the frequency of the output also varies inversely.

Power Dissipation

The maximum power dissipated from ICs will be calculated based on data from the datasheets.

Supply current ***	I_{CC}	—	2.5	6	mA	VCC=5.25V

Figure 19: 74LS112N Max Current [5]

I_{CC}	$V_I = V_{CC}$ or 0, $I_O = 0$	6 V	8	160	80	µA

Figure 20: 74HC595N Max Current[6]

I_{CC}	$V_I = V_{CC}$ or 0	$I_O = 0$	6 V	80	µA

Figure 21: 74HC164N Max Current[7]

I_{CC} Supply current	V_{CC} = MAX, See Note 2	30	43	30	50	mA

Figure 22: 74LS86N Max Current[8]

Supply current	Output low, No load	V_{CC} = 15 V	10	12	10	15	mA
		V_{CC} = 5 V	3	5	3	6	
	Output high, No load	V_{CC} = 15 V	9	10	9	13	
		V_{CC} = 5 V	2	4	2	5	

Figure 23: NE555 Max Current[3]

IC	Max Current	Figure	Vcc	Quantity	Power Consumed
74LS112N	6 mA	16	5	2	60 mW
74HC595N	0.08 mA	17	5	1	0.4 mW
74HC164N	0.08 mA	18	5	1	0.4 mW
74LS86N	50 mA	19	5	1	250 mW
NE555	6 mA	20	5	1	30 mW

Total Power Consumed by ICs is 340.8 mW. For the power consumed by the driver + load,, I connected the motor + motor driver across my power supply at 5 Volts:

Figure 24: Load Power Consumption

Total Power Consumed by driver + motor = 1787 mW

Total Power Consumed = 2127.8 mW

These circuits are driven by barrel jack power supplies connected to the mains and hence do not require battery replacement.

Cost

I did not buy the university provided kit, all my parts were sourced from AliExpress and reference costs will also be taken from AliExpress. All costs reported in Canadian Dollars.[9]

Part Name	Quantity	Cost
MB102 Power Supply[10]	2	3$*2 = 6$
SN74HC595N[11]	1	0.3$
SN74LS112N[12]	2	0.35$*2 = 0.7$
SN74HC164N[13]	1	0.3$
SN74LS86N[14]	1	0.25$
5.1k Ohm Resistor[15]	1	0.03$
2k Ohm Resistor[15]	1	0.03$
10k Ohm Resistor[15]	1	0.03$
2.2uF Capacitor[16]	2	0.03$*2 = 0.06$
0.1uF Capacitor[16]	1	0.03$
Arduino Joystick Module[17]	1	3$
ULN2003 Driver Board[18]	1	2$
28BYJ48 Stepper Motor[18]	1	2$
Long Breadboard Wires[19]	~14	0.5$
Small Breadboard Wires[19]	~32	0.5$
830 Tie-point Breadboard[20]	2	4$*2 = 8$

Total Cost = 25.35$

YouTube Video

https://youtu.be/WpjY3gYZrNc

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