# ECE 445

Fall 2017

# Semiconductor Contact Probe Aligner

Zehua Chen, Stanford Zhou, Zihao Xie
TA: Rebecca Chen

# Abstract

Our semiconductor probe aligner replaces the manual, hands on control of the probe station Signatone S-725 positioners, with a more precise and convenient electronic control. The project aims to reduce human error made when attempting to align and place the probes tips on a semiconductor device for measurement. By preventing these errors, our project guarantees that neither the probe tips nor the semiconductor wafer will be damaged in the process of probe alignment.

Our project turned out as mostly successful, as most of our proposed features are implemented to some capacity. Other than the power circuit, all of our modules performs as expected.

This report explains the intuition behind our project, the high-level layout and design of our project, the requirements and verifications, the costs and distribution of workload, and the uncertainties and future improvements of our project.

# Contents

# 1.Introduction

As semiconductor technology improves, the size of each device in the wafer is decreasing exponentially. Even though in industry the measurements of semiconductor devices at the micro and Nano level are handled electronically, students and researchers on campus still use lab equipment mainly controlled manually by hand. One of the more challenging measuring instruments to handle is the probe station, which is used in the IC fabrication lab class here. Usually, semiconductor devices are on the scale of micrometers. Thus, navigating the probes by hand requires the user to have experience and high precision. In addition, noticing the probe is in contact with the wafer with bare eyes, even with the help of a microscope, can be difficult. A mistake in either way can scratch the device and even damage the probes, disabling the probe station.

To solve these problems, we introduce this project that will control the movement of the probes electronically with motors and a computer interface. Our project stops the probes from pressing into the wafer, so the probes won't bend, differentiates metal from non-metal so the probes will be placed at the right place, and prohibits all movement in the horizontal plane when probe is in contact with the wafer so the wafer won't be scratched. The user will use the computer as the interface to control the motors on the high level. With our features and electronic control, we can alleviate a lot of risk involved in the measurement of semiconductor devices using the probe station.

The core of the original instrument is the four probes, which serve to connect the metal contacts of the source, drain, body, and gate of an MOS device. The probe station can also measure other integrated circuit devices such as capacitors. Since the probes are measuring integrated circuits at the micron scale, the probe tips are very fragile. And once they are bent or blunt, the measurement results will be affected drastically. In Spring 2017 semester's IC fabrication lab, two of the three probe stations used to measure the wafers were disabled; during earlier sections, some students bent the probes while trying to get measurements. As a result, most of the students taking the class that semester didn't get the right data.

Furthermore, the sharp probes can easily damage the devices on the wafer if not handled carefully. When students make the semiconductor devices, each deposition level is on the scale of nanometers, and the metal contacts are micrometers in thickness. If students don't have a lot of devices on their wafer, losing some devices due to scratching can be a serious problem as well. Note that this project is not done under the behalf of a certain professor.

Figure 1 is the micro-positioner. The red circle indicates the probe tip holder position. The circle on the right indicates the knobs used to control the motion of the probe. The currently used probe tip holder is the U-E Style Probe Tip Holder. The side views of the micro-positioner and U-E Style Probe Tip Holder are provided below in Figure 2 from the data sheet. The radius of the knob is 1 centimeter. The accuracy of the knob control is 5 microns by the leadscrew drive in all three dimensions. The covering area is 1.27cm x 1.27cm. By measurements, the knob x will change the probe x position by 30 microns per 360-degree. The knob y will change the probe y position by 30 microns per 360-degree. The knob z will change the probe z position by 20 microns per 360-degree.

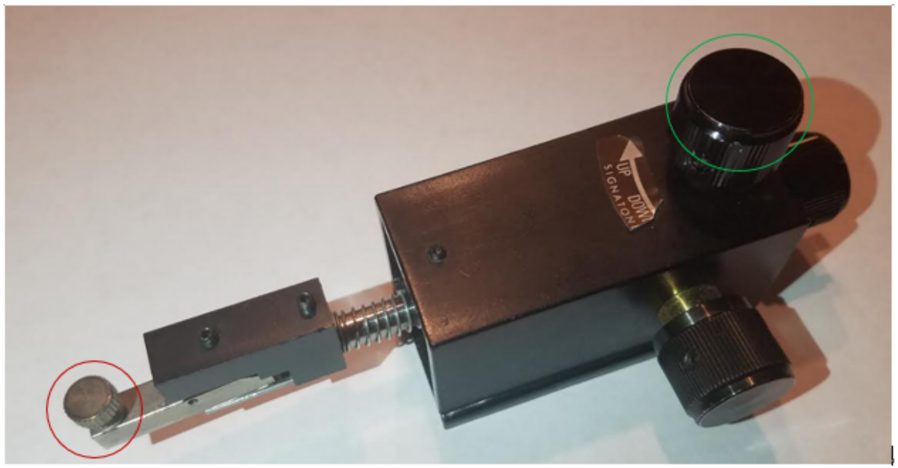


Figure 1 Actual Image of Positioner.

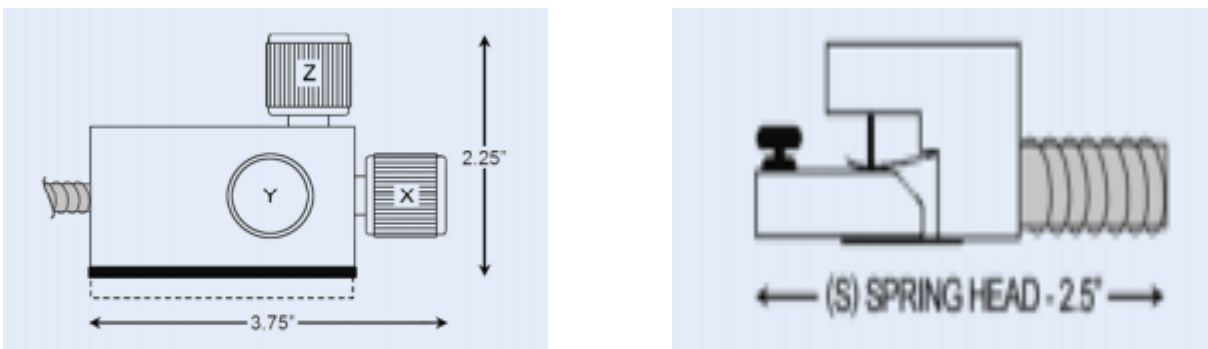



Figure 2[1] horizontal side views, [2]probe tip holder

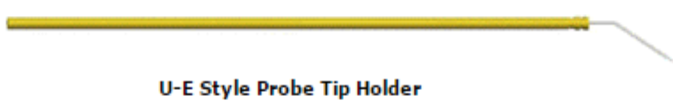



Figure 3 Probe Tip.

# 2.Design

## 2.1 Block Diagram

The block diagram for our design is shown in Figure 4. Our complete design is partitioned into the sensor unit, control unit, motor unit, computer, user interface unit and power supply. The motor unit is attached to the three manual knobs and enables the movements of probe tip in three dimensions at two different speeds. The sensor unit is mainly responsible for determining whether the probe tip has contact with the wafer and for recording the images seen through the microscope. The user interface unit provide users with live image of the probe tip and wafer in the microscope so that users know where the probe tip should be moved to. It also creates an electronic control of motors to replace manual control. The power supply unit provides power to other components of design. At beginning of the semester, four square wave signals that are needed to run the stepper motor are generated by Arduino. In the end, Arduino is only responsible for transmitting movement instructions from computer to FSM. The generation of those four square-wave signals are done by our own circuit.

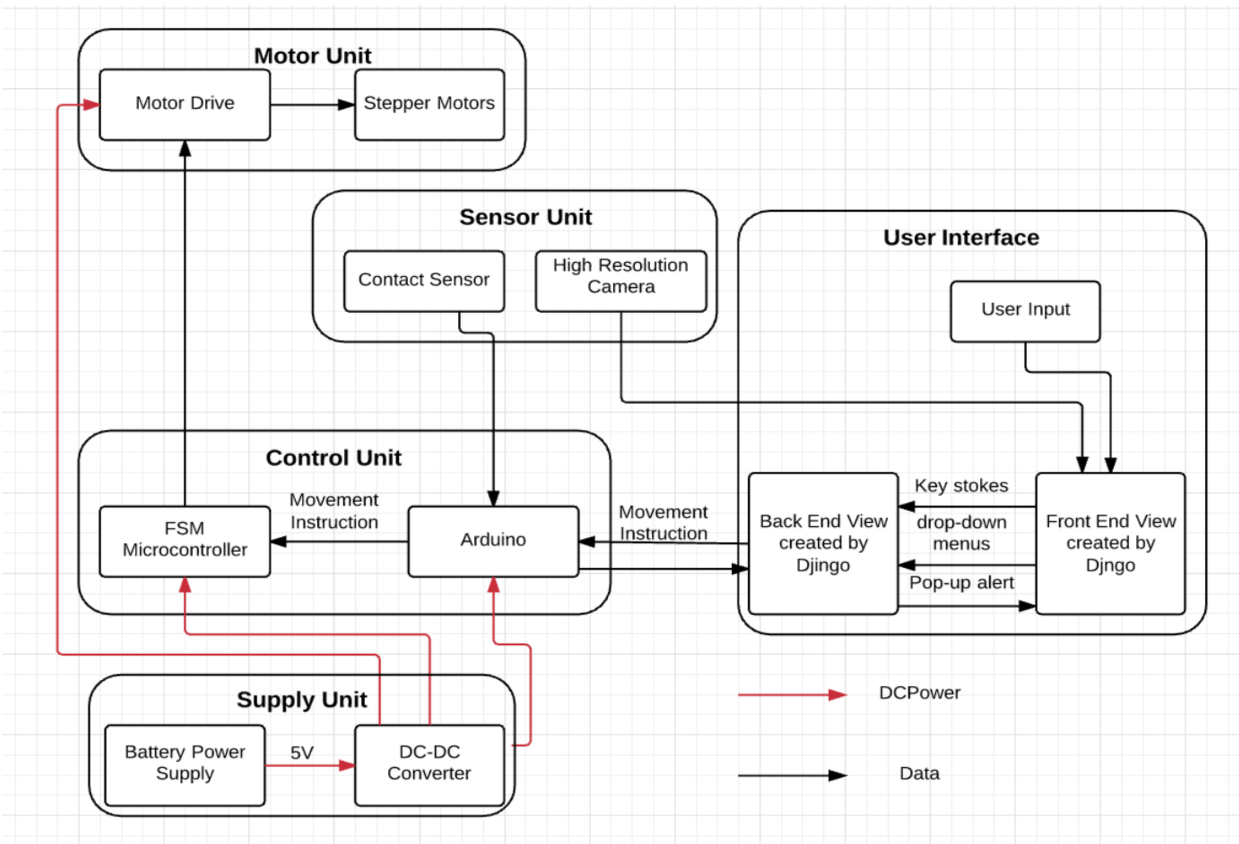



Figure 4. Block Diagram.

## 2.2 Motor unit

### 2.2.1 Design Procedure

There are three knobs to control a probe positioner. Each knob is responsible for one dimension of movement. Therefore, the motor unit contains three stepper motors to replace those three manual control knobs respectively to achieve electronic control.

The most important part of motor unit is choosing the right motor. The original motor that was going to be used is standard NEMA-17 stepper motor, which can provide six times the torque produced by the current motor. However, NEMA-17 is much larger than the current one and it needs an additional separate gearbox to meet accuracy requirement, which again increases the size of motor unit. Since we need to fit three motors of choice onto one probe positioner, the NEMA-17 motor can't be used for our project. Instead of using NEMA-17, we chose a smaller sized stepper motor with adequate torque which also have a built-in gear box to fulfill accuracy requirement. Torque is sacrificed to reduce the size of motor so that it is much easier to physically attach three stepper motors to probe positioner. In addition, the small motors reduce power consumption.

We performed torque and accuracy tests to examine the feasibility of the stepper motor. A 200g object and a ruler are used to measure the static torque of knobs of positioner. The torque is calculated with Equation (2.1).

$$\tau = Fl = mgl \tag{2.1}$$

A digital electronic ruler is used to measure total probe tip displacement of rotating knob 15 revolutions and corresponding Equation (2.2) relates the displacement of the probe to the amount of rotation in terms of degrees.

$$x = \frac{displacement\ \ one\ revolution}{360^\circ} \times angle \tag{2.2}$$

### 2.2.2 Design Details

Static torque of probe knob is measured by using a 200g object to rotate the probe knob. The static torque by Equation (2.1)

$$\tau = mgl = 0.2kg \times 9.8m/s^2 \times 0.5cm = 0.98N \cdot cm \tag{2.3}$$

The maximum holding torque of stepper motor is 3.9 N/cm. Therefore, the stepper motor is suitable for our design.

According to data sheet of the stepper motor [1], it has 1024 steps per revolution. The probe tip moves 30 µm when the knob rotates one revolution. Before replacing manual knobs with stepper motors, we assume that the least amount of rotational angle a person can manually rotate is 2 degrees. The corresponding probe tip displacement by Equation (2.2) is

$$x = \frac{30\mu m}{360^\circ} \times 2^\circ = 0.17\mu m \tag{2.4}$$

With the stepper motor, the probe tip displacement for one step corresponds to

$$x = \frac{30\mu m}{360^\circ} \times \frac{360^\circ}{1024 steps} = 29nm/step \tag{2.5}$$

Therefore, after using stepper motor, our design is almost 6 times better than the manual control before

$$\frac{0.17\mu m}{29nm} = 5.9 \tag{2.6}$$

This improvement is important to our accuracy requirement. This means that we can control the probe tip displacement in a much smaller scale. Also, the user has a larger margin of error if the probe tip is very close to the wafer.

Each stepper motor is controlled by one SN754410 H-bridge drive [2]. The schematic is shown in Figure 5. The motor drive receives four digital input signals to energize four phases of stepper motor accordingly. The speed of stepper motor is controlled by the frequency of digital signals. The direction of stepper motor is controlled by the energizing sequence of digital signals.

In order to figure out signals required to rotate the stepper motors, drive circuit is connected with Arduino. By using stepper.h [3] library, four digital input signals are measured on oscilloscope to see what kinds inputs are needed. The measured waveforms can be seen in Figure 6 and Figure 7. The speed of stepper motor with different frequency is shown in Table 1.

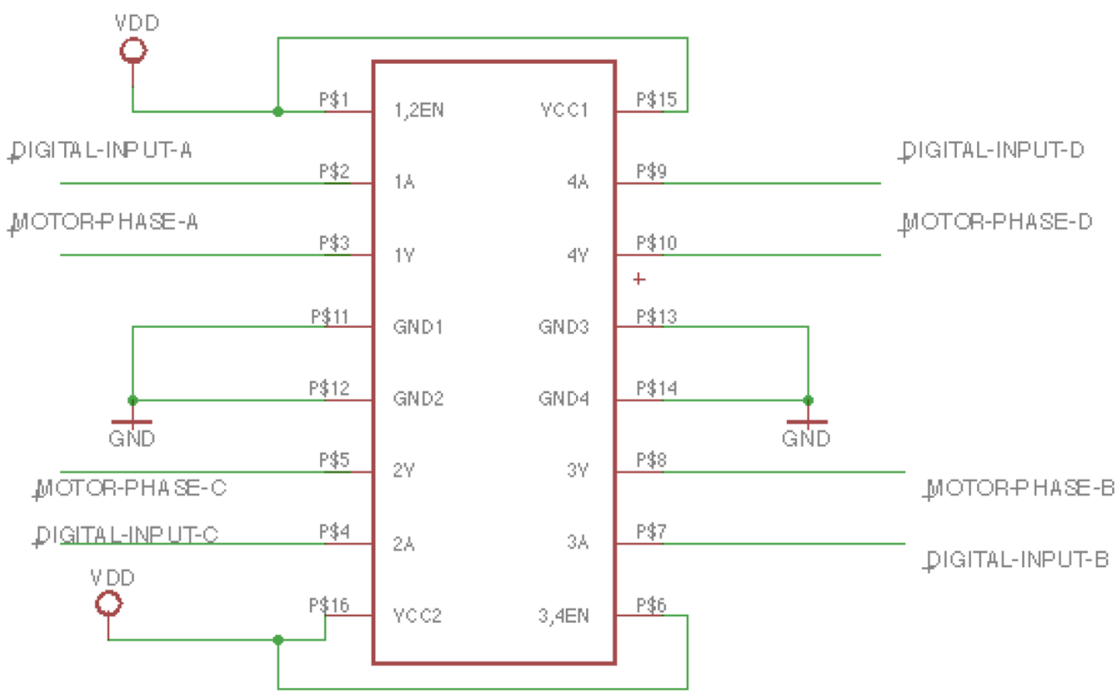



Figure 5. Stepper Motor Drive Circuit.

Table 1 Speed of Motor with Frequency of Input Signals

| | | | |
|---|---|---|---|
| Frequency (Hz) | 0.25 | 2 | 4.25 |
| Speed (steps/s) | 1 | 8 | 17 |


Figure 6. Input signals of Clockwise Movement of Stepper Motor.

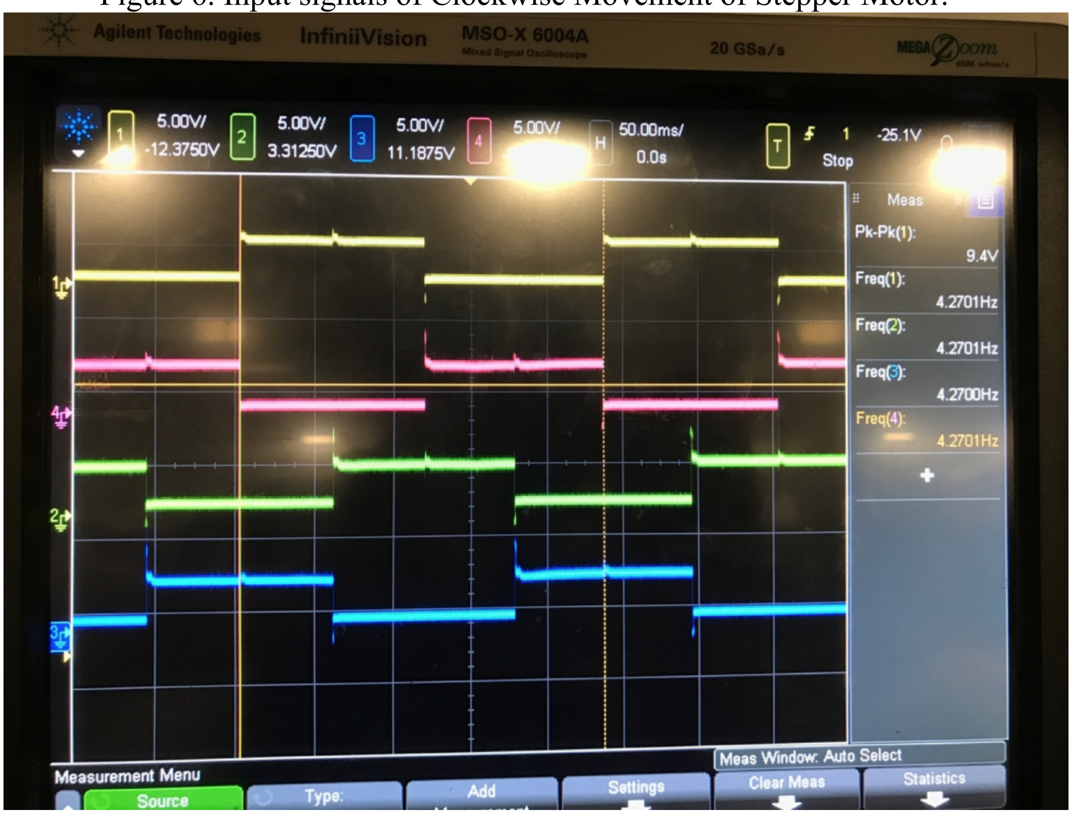



Figure 7. Input signals of Clockwise Movement of Stepper Motor.

## 2.3 Control unit

### 2.3.1 Design Procedure

The control unit should be able to generate the desired signal for motor driving circuit and control the movement of the motor according to the six bits input from user interface. The signal generator circuit contains two parts. First, a clock signal is generated using time delay chip. Second, the clock signal will pass the control circuit and be fed to the flip-flop circuit to generate the desired signal for the motor driving circuit. There are several alternative approaches to generate the signal such as using Arduino motor library and function generator. However, the cost of those approaches are much more expensive than our design choice.

For the control circuit, finite state machines (FSM) are implemented to achieve the functionality [4]. The control circuit contains three FSMs: speed selection, probe selection and motor selection. Those FSMs are implemented by basic logic gates such as AND gates and NOT gates. The functionality of those FSMs are equivalent as multiplexers(MUX) and demultiplexers (DEMUX). Instead of buying off-shelf products, our implementation gives more freedom to arrange the circuit as well as omitting redundance to reduce the cost of the project.

### 2.3.2 Design Details

The detailed design of clock signal generator circuit utilizes the property of 555-time delay chip [5]. The circuit diagram is shown in Figure 8.

The left side is a RC circuit. The capacitor will charge toward 5 V. As the voltage at the threshold pin increases to two thirds of 5v. The output will be low. Then, the discharge pin will discharge the capacitor. When the voltage at the trigger pin decreases to one third of 5v, the output will be low. Therefore, a clock signal is generated at the output pin. The frequency of the output signal is calculated by Equation (2.7).

$$f = \frac{1.44}{C_1(R_1 + 2R_2)} \tag{2.7}$$

To achieve output frequency of one Hertz, R1 is set to 1000 Ohm. R2 is set to 6500 Ohm. C1 is set to 100 Microfarad. To achieve output frequency of eight Hertz, R2 is changed to 8500 Ohm and C1 is changed to ten Microfarad. Both one Hertz and eight Hertz signals are generated at the same time by two sets of signal generator circuits. Then, they will be passed into the speed selection FSM.

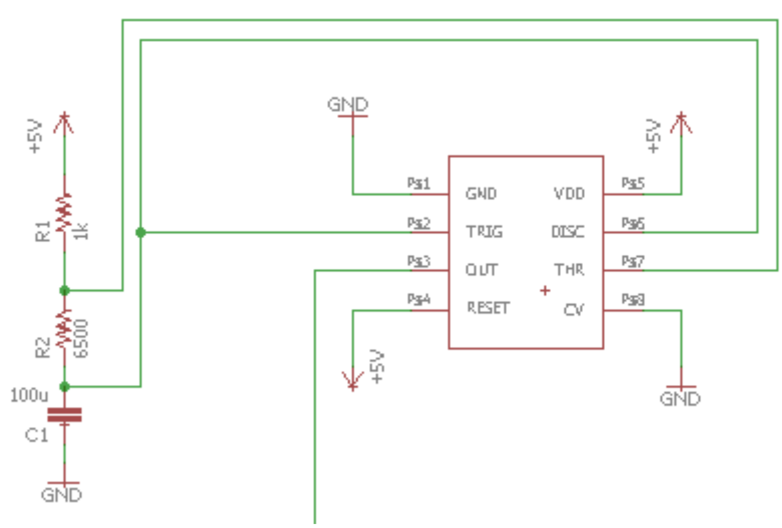


Figure 8. Clock Signal Generator Circuit.

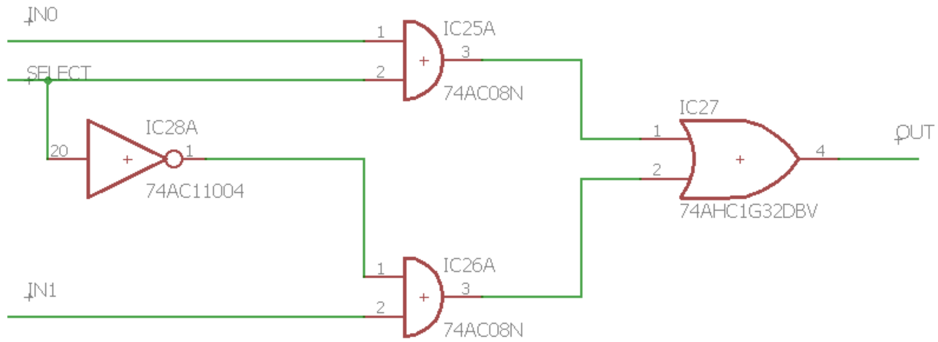


Figure 9. Two to One MUX Circuit.

The speed selection FSM is a two to one MUX. The circuit diagram is shown in Figure 9. The user interface will pass the select signal to the circuit and IN0 and IN1 are outputs from the clock signal generator circuits. Then, the output of the two to one MUX will be passed into the probe selection FSM.

The probe selection FSM has the same structure of FSM for motor select. The only difference is that four states are corresponding to selection of four different probes. However, for the simplicity purpose, only one of the probe selection state is implemented. The other three states are duplications of the implemented one.

The motor select FSM contains four states. The state diagram is shown in Figure 10. S2 is the first motor activated state. The first motor controls the probe motion on z-axis. S3 is the second motor activated state. The second motor controls the probe motion on the x-axis. S4 is the third motor activated state. The third motor controls the probe motion on the y-axis. S1 is motor deactivated state. In this state, all motor motions will be prohibited. The initial state will be S1.

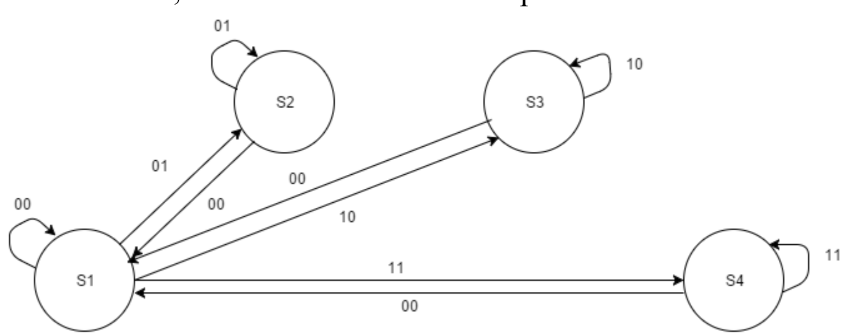


Figure 10. State Diagram of Motor Select FSM.

The actual implementation of the FSM is a one to four DEMUX. The top-level diagram is shown in Figure 11. The C1 and C0 signals correspond to two-bit digital motor select signal from Arduino board. The S1, S2, S3, S4 signals correspond to four states in the FSM. The Din signal is connected to the output of probe select FSM as an input digital signal.

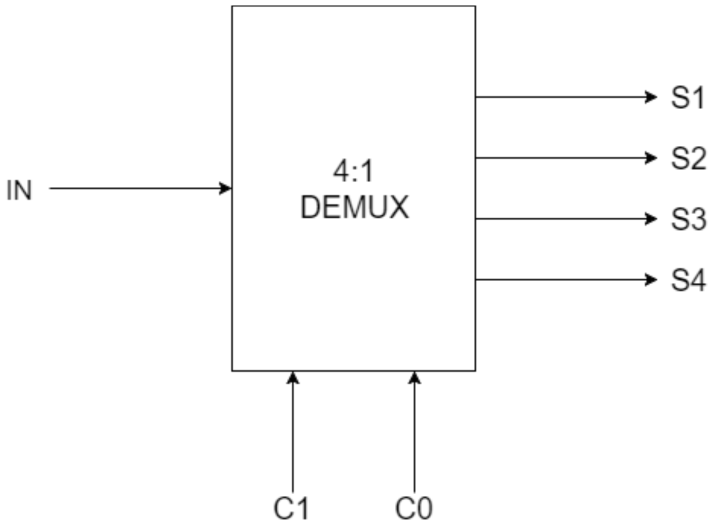


Figure 11. Top-level Diagram of Motor Select FSM.

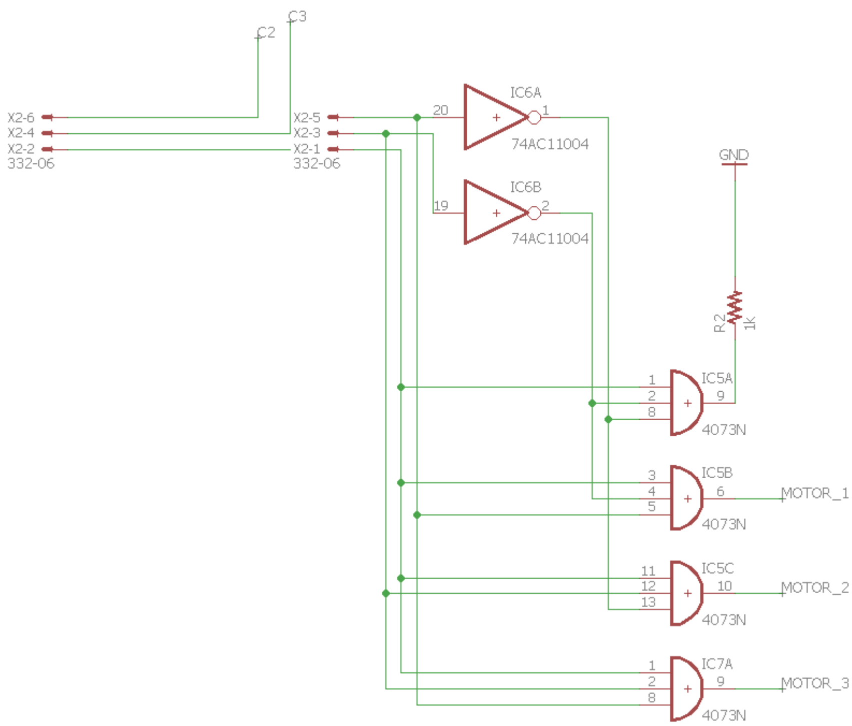


Figure 12. Circuit Diagram of Motor Select FSM.

The circuit diagram is shown in Figure 12.

The output signal which is a clock signal will be passed into the flip-flop circuit to generate the desired output for the motor drive circuit [6]. One bit from the user interface will be utilized as the direction control. The output signal from the motor selection FSM is used as the clock signal for the D flip-flops. The output of the first flip-flop will pass through the XOR gate with the direction control bit to the input of the second flip-flop. The inverse output of the second flip-flop will pass through the XOR gate with the direction control bit to the input of the first flip-flop. Then, the output and inverse output of the two flip-flops are the desired signal to the motor drive circuit. The circuit diagram is shown in Figure 13.

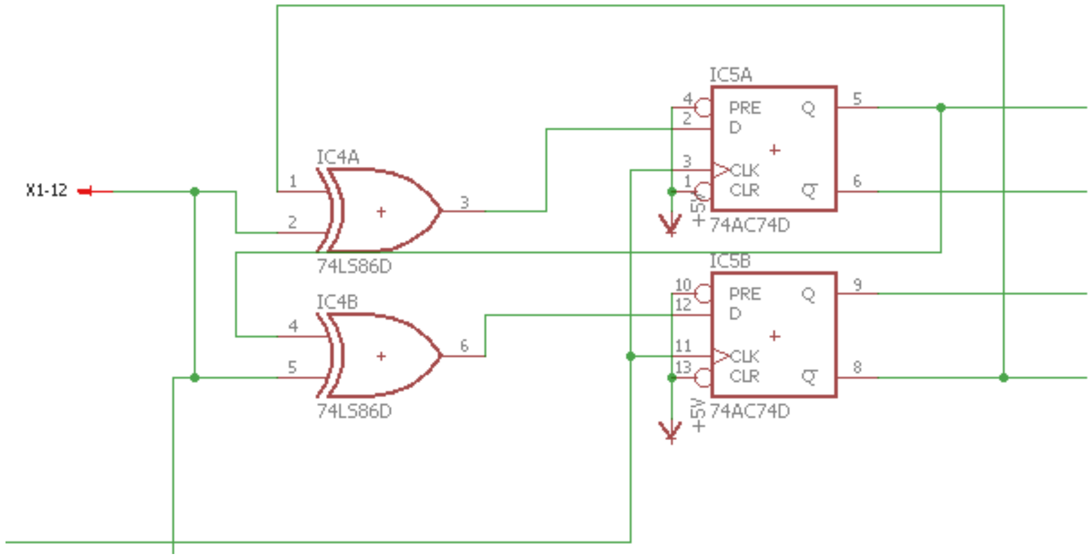



Figure 13. Circuit Diagram of D Flip-flop Signal Generator.

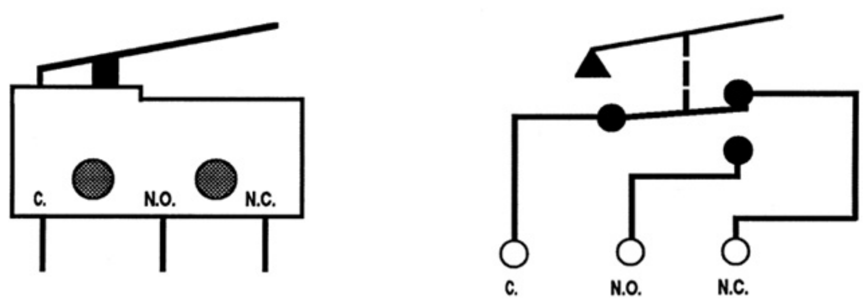



Figure 14. Micro Switch Circuit Schematic.

The overall integrated circuit diagram is shown in Appendix B.

In order to detect whether the probe tip touches the metal contact, we will use a micro switch Figure 14.

When no downward force is applied to the top lever, current flows through the Normally Closed(N.C.) circuit powered by node C. When there's a downward force lifting the lever, current flows through the Normally Open(N.O.) circuit.

The entire probe tip handler on the right will shift down when the corresponding probe knob turns to the vertical downward position. We will attach a handle underneath the probe tip handler as shown above, and we will place the micro switch directly beneath the handle. Once the probe handler is lowered to a certain position, the micro switch will trigger. We will make sure it triggers as the position of the probe tip reaches the device. Since in the real probe station, the vertical position of probe positioner and the wafer platform doesn't change, this is achievable. The N.O. circuit will be connected to the control unit and the user interface. Once there's current detected from the N.O. line, the control unit will disable all of the possible movements except moving up vertically. A signal will also be sent back to the user interface via arduino notifying the user that the probe tip is in contact with the device.

## 2.4 User Interface

### 2.4.1 Design Procedure

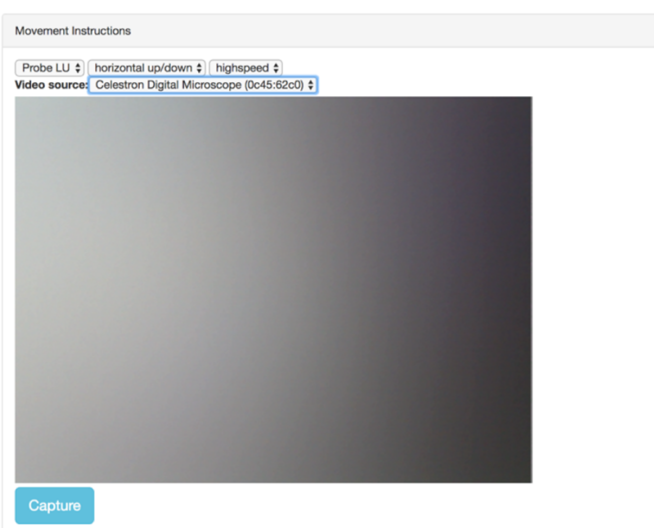
The user interface webpage is made with Django framework [7], because the framework is user friendly and the python based back-end is flexible. There are many replacements for the web page framework, but the libraries python provides are more resourceful compared to that of a Java or C++ based back-end. In order to send signals from the web page to the control unit, we used an Arduino Mega as the interface. We chose to use Arduino Mega because we can control the digital pin outputs with the pyFirmata library [8] from python. In fact, almost all the available Arduino have the Standard Firmata protocol, but we chose the Arduino Mega because it has much more digital output pins compared to others, which will satisfy the needs of the control unit.

### 2.4.2 Design Details

The user interface webpage is shown below in Figure 16.1. The user will control the parameters of probe alignment with the drop-down menus; probe number, dimension of movement, and speed respectively. Below the drop-down menus is the camera stream of our Celestron Digital Microscope Imager 44421. Since we couldn't get permission to access the microscope, the stream of the imager is blurry.

Before placing a probe to a metal contact region, the user has to locate the region where he/she intend to align at the center of the stream and press the capture button. The button will send the snapshot of the image to an image processor, which will determine whether the region is metal or nonmetal. If the region is nonmetal, a pop-up window(Fig.16.2) will tell the user to select another region.

To control the movement of the probes, the user will press the D and A keys for forward and backwards movement of the probe knobs. Every time one of keys A or D is pressed, the user interface will update the digital output pins. Figure 17 shows my code for sending the information of the drop-down menus and the key input when a key is "pressed", and sending default values when key is "lifted".



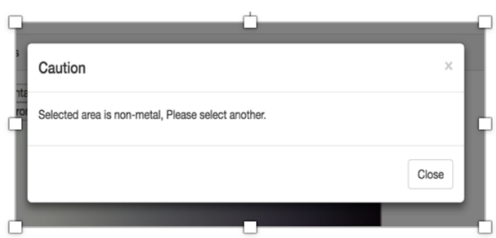




Figure 16.1User Interface Webpage, 16.2Pop-up alert window

```javascript
$(document).ready(function(){
  console.log(keyEnable);
  $(window).keypress(function(e){
    var key = e.key;
    console.log(key);
    if(key == "a" || key == "d"){
      if(keyEnable == 1){
        var data = {}
        data["key"] = key;
        data["probe_no"] = $("#probe_no").val();
        data["direction"] = $("#direction").val();
        data["speed"] = $("#speed").val();
        data["csrfmiddlewaretoken"] = getCookie('csrftoken');

        // csrf_token
        $.ajax({
          type: "POST",
          url: "/probe/instruction/",
          data: data
        });
      }
    }
  });
  $(window).keyup(function(e){
    var data = {}
    data["key"] = "none";
    data["probe_no"] = "none";
    data["direction"] = "none";
    data["speed"] = "none";
    data["csrfmiddlewaretoken"] = getCookie('csrftoken');
    $.ajax({
      type: "POST",
      url: "/probe/instruction/",
      data: data
    });
  });
});
```

Figure 17. JavaScript code

Specifically, the digital output pins 23 and 25 are for probe selection, pins 27 and 29 are for motor selection or dimension, pin 31 is for speed control, and 33 is for output control.

To process the image after the capture button is pressed, we used the OpenCV library [9], which has an abundant amount of image processing functions. First, we access the pixels of the given image, and locate the center region. Then we count how many pixels' BGR average value are higher than a certain threshold, in this case 150. If two thirds of the pixels' value are higher than the threshold, we determine the center region consists of metal.

User Interface also takes an analog input from the micro switch control circuit. When the micro switch signal is high, the user interface will disable all motion other than vertically upwards, to prevent the user from damaging the probe tip or scratching his/her wafer.

## 2.5 Power supply

### 2.5.1 Design procedure

All of the TTL chips and FSM control needs 5 V input and small size stepper motor needs 5 V input too. Therefore, 5 V output power supply is needed. There are lots of ways of building a 5 V

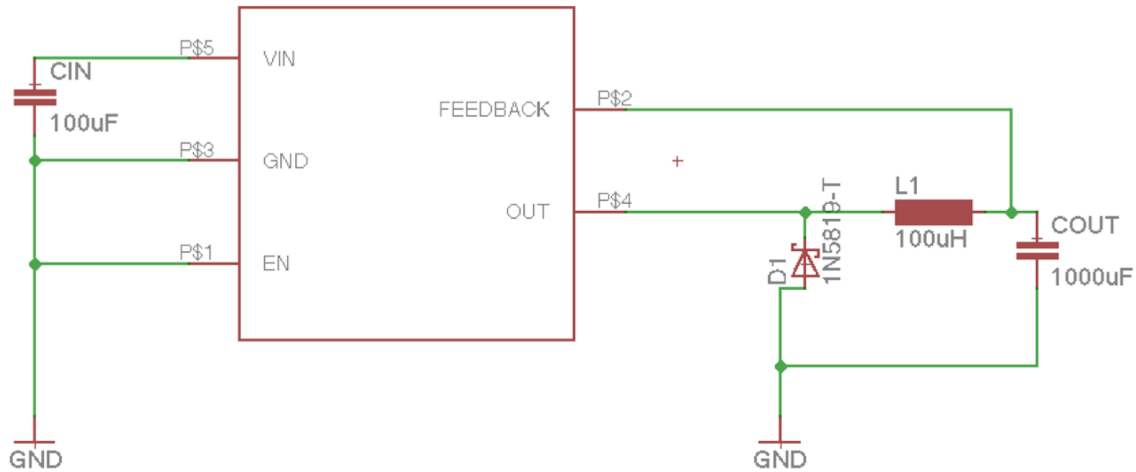



Figure 18. Simple High-Efficiency Step-down (Buck) Regulator.

output. Buck converter and boost converter are some choices. Since boost converter will have much larger current, step-down (Buck) regulator is chosen.

### 2.5.2 Design detail

The design consists of a 9 V battery and a simple high-efficiency step-down (Buck) regulator. A LM2576 chip [10], 1N5822 diode and some passive components are used. The circuit is shown in Figure 18.

# 3. Verification

Overall, most parts of our project turned out well. The basic requirements, such as motor movements, user interface and control unit logic, and correct signal generation from the control unit. It is safe to assume that the base features of our project, probe positioner movement with enhanced precision, is ready for practical use.

The overall worst case delay (occurs when users change the direction of movement) of the of our project, from keyboard to the movement of motors, is around 0.5 seconds. The main cause of this delay is when the direction of rotation is switched for the motor, the current flow driving the motor has to invert as well.

The overall power consumption of the circuit is 6.5 W. Our circuit is driven by constant 5 V, and the current output of our circuit is 1.3 A based on our measurement from the Multimeter. We calculated the power consumption based on Equation (3.1) below.

$$P = UI \tag{3.1}$$

## 3.1 Verification of Motor Unit

There are two requirements of motor unit. They are stated in Appendix A. During the testing, three stepper motors can easily rotate according to direction and speed specified by user. They successfully take over manual control. They can stop immediately if movement is not allowed by user.

## 3.2 Verification of Control Unit

The verification of the control unit is done by connecting the output and inverse output from the control unit to the oscilloscope. The data is shown in Figure 19.


Figure 19. Generated Square Wave.

Also, the FSM component of the motor is tested by different input combinations and measures the output voltage.

All of the requirements for the control unit are met. For more information on those requirements and how they are verified, please refer to Appendix A.

### 3.3 Verification of User Interface

From our measurement, the delay of the data transmission for the PC to the Arduino is minimal. Since in our code I stop the movement once the key is lifted up, the delay is mostly the time a user takes to lift up his/her fingers. This is tested and verified by connecting the output pins of the Arduino with LEDs on a breadboard.

All of the requirements for the user interface are met. For more information on those requirements and how they are verified, please refer to Appendix A.

### 3.4 Verification of Power Unit

The requirement for this power supply is that it can maintain a stable 5 V output voltage and it should not fluctuate more than 0.3 V. Our power supply can maintain at 5.04 V and supply power to all control circuits. However, when the motor is controlled to rotate, current exceed maximum output current limit 3 A and thus the chip got overheated. Therefore, a good solution is to build two identical power circuits for both control circuit and motor circuit.

# 4. Cost

Our individual development costs will be 40 dollars/hour, 10 hours a week for each the three of us. We spent 10 weeks of the semester on this project. The labor cost of project is

$$ideal\ salary(hourly\ rate) \times actural\ hours\ spent \times 2.5 \tag{4.1}$$

So our total development cost this semester by using Equation (4.1) is

$$40\frac{dollars}{hour} * 10\frac{hours}{week} * 10weeks * 3\ * 2.5 = 30000 \tag{4.2}$$

Table 2 Bulk-purchase Cost of Project

| **Part** | **Cost** |
|---|---|
| Celestron Digital Microscope Imager 44421 | \$51.99 |
| Arduino Mega 2560 Rev3 | \$38.50 |
| Three Stepper motor - 24BYJ24 | \$14.95 |
| SN754410 Quadruple Half-H Driver | \$30.24 |
| LM2576xx Series SIMPLE SWITCHER® 3-A Step-Down Voltage Regulator | \$8.58 |
| Texas Instrument CD74AC139M96 Dual 2-to-4 Line Decoder/Demultiplexer | \$16.99 |
| 10PCS Texas Instruments CD4081BE CD4081 CMOS Quad 2-Input AND Gate | \$9.98 |
| Elegoo 17 Values 1% Resistor Kit Assortment, 0 Ohm-1M Ohm (Pack of 525) | \$10.86 |
| Two TPS799 200-mA, Low-Quiescent Current, Ultralow Noise, High-PSRR Low-Dropout Linear Regulator | \$10 |
| Three SN754410 Quadruple Half-H Driver | \$6 |
| 25 Pieces of CD4013 CD4013BE CMOS Dual D-Type Flip Flop DIP14 | \$35 |
| Texas Instruments SN74HC04N Hex Inverters (Pack of 10) | \$8 |

Therefore, our total development cost will be 30252.12 dollars. Our project is commercially viable, because bulk-purchase cost is roughly 250 dollars. Compared with the cost of damaging wafer and probe tip, this investment money is reasonable and acceptable in semiconductor lab.

# 5.Conclusion

## 5.1 Accomplishments

We accomplished electronic control on the semiconductor probe aligner, and the precision requirement we promised in our proposal. Our user interface, control unit, and motor unit are successfully integrated together. The micro switch protection feature also works if the micro switch is placed correctly. Therefore, our wafer and probe tip protection feature is also achieved.

The delay is noticeable but should not be a problem in performance, and our project, given an adequate voltage source, can be used extensively with no time constraint.

## 5.2 Uncertainties

Even though we accomplished most of our features, there are uncertainties in our project. First, because none of us have access to the semiconductor probe station, we can only predict how our project will perform as a product. The speed options we chose for probe movement might not be practical. And the image processing function is purely theoretical; since we have no access to images of semiconductor devices under a microscope, we have no idea if the threshold value or even the function itself is viable for use. Battery is our power supply, so the whole design may not function correctly after the battery is dead. Also, since our power circuit does not have a heat sink, the thermal problem may be an issue after a long time of operation.

## 5.3 Future work

In the future, we hope to test our project on the actual probe station, and enhance our project based on the results. Especially the image processing function and the speed selection mentioned above.

We want to put all the circuit design on a PCB board in the future. It will make the project more compact and cheaper.

Power circuit should be broken into two identical power circuits for both control circuit and motor circuit. Also, a heat sink is helpful to solve the thermal problem of chip.

## 5.4 Ethical Considerations

During the demo, our power unit burned out. According to the #1 of IEEE code of ethics[11]. The power unit should be redesigned and tested to make sure that it does not harm the public. Also to comply with the #7 of IEEE code of ethics, we admit the error in our design and accept honest criticism from other people[11]. We will improve our design and correct the issues with our power unit.

## References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# Appendix A Requirement and Verification tables

## For User Interface

| Requirements | Verification | Success |
|---|---|---|
| **1**: After a valid key(A, D) is pressed, the front-end html file will send all the information of the drop down menu selection, along with the key information to the back-end view. | 1.Print the necessary parameters on the console or the terminal. The output is correct. | Yes |
| **2**: The logic of the Arduino pins is correct, given the key input. The pins are digital pins 23/25(probe number), 27/29(dimension of movement), 31(speed), and 33(key). Our output logic for default state is all 0s for the pins above. | 2. Use LEDs connected to the pins mentioned above. Press the correct keys and see if the correct LEDs are on. The output high of the digital pins are set to around 5v, enough to drive the LEDs. | Yes |
| **3**: The camera is correctly streamed on the webpage along with the drop-down menus. | 3. Once the cameras are plugged in, and all the necessary command line codes are run. The webpage containing the drop-down menus and microscopic camera view can be loaded. Check if when we run serve and open localhost//:8000, the camera stream is there. | Yes |

| | | |
|---|---|---|
| **4**: User must press the capture button before moving the probes. After the capture button is pressed, the snapshot image of the stream is sent to the back-end. | 4. Test the outputs of the digital pins before pushing the capture button with LEDs; they should all be at logic 0. I will display the image to make sure this part is correct by loading the image to the console. | Yes |
| **5**: The image is sent to the image processing function and processed correctly. The image is either mostly metal, where the User Interface will activate the keyboard for movement, or mostly nonmetal, where the User Interface will alert the user with a pop-up window. | 5. Feed the processing function an image of my choosing and print out the result (lightly colored or dark). If the middle of the image frame contains metal, then we can move the probes. | Yes, but uncertain to practical testing, and will need further improvement to be applicable. |
| **6**: The pop-up window should come up whenever the user chooses an invalid, non-metal heavy picture. The logic should be correct. The pop-up window should alert the user and make him/her choose another region to place the probes. | 6. For the logic portion, I will insert print statements inside my program where the pop-up menu is requested. The pop-up menu can be verified by looking at the screen and check if after removing the pop-up, the user can choose another region. | Yes |

## For Control Unit

| Requirements | Verification | Success |
|---|---|---|
| 1. The output of the probe selection demultiplexer matches the desired control state truth table 1. | 1. Manually connect the C0 and C1 to different logic combinations and check the LED. The LED lights up according to the correct logic. Therefore, the implementation is successful. Ensure the logic high voltage is 5±0.5v. | Yes |
| 2. The output of the motor selection demultiplexer matches the desired control state. | 2. Manually connect the C2 and C3 to different logic combinations and check the LED. The LED lights up according to the correct logic. Therefore, the implementation is successful. Ensure the logic high voltage is 3.5±0.3v. | Yes |
| 3. The output of the speed selection multiplexer matches the desired control state and output waveform. | 3. Manually connect the C4 to different logic combinations and check the waveform at output. When C4 is logical low, the output is a (0.25 ± 0.05)x4 Hz and 50% ± 2% duty cycle square wave for slow motion. When C4 is logical high, the output is a (2.0 ± 0.05)x4 Hz and 50% ± 2% duty cycle square wave for slow motion. | Yes |

| | | |
|---|---|---|
| 4. The 555-signal generator circuit produce 0.25x4 Hz and 50% duty cycle square wave for slow motion and 2x4 Hz and 50% duty cycle square wave for fast motion. | 4.<br>(a) Manually connect the output to an oscilloscope.<br>(b) Ensure the voltage high is 3.5 ± 0.3v.<br>(c) Ensure the voltage low is 0 ± 0.1v.<br>(d) Ensure the duty cycle is 50% ± 2%.<br>(e) Ensure the frequency is (0.25 ± 0.05)x4 Hz for slow motion and (2.0 ± 0.05)x4 Hz for fast motion. | Yes |
| 5. The motor signal generator produce desired output waveform to drive the motor. Also it can control the forward and backward movement by control signal. | 5.<br>(a) Manually connect the output to an oscilloscope.<br>(b) Ensure the phase one signal have correct frequency and duty cycle.<br>(c) Ensure the phase two signal have correct frequency and duty cycle.<br>(d) Ensure the delay is within 1ms.<br>(e) Ensure the motor is moving forward when the control signal is 0 and moving backward when the control signal is 1.<br>(f) Ensure the frequency is 0.25 ± 0.05 Hz for slow motion and 2.0 ± 0.05 Hz for fast motion.<br>(g) Ensure the duty cycle is 50% ± 2%. | Yes |

## For Motor Unit

| Requirements | Verification | Success |
|---|---|---|
| 1.With 0.5Ncm of loading torque, three motors are still able to move at a very slow speed. This requirement enables us to control movement of probe knobs and achieve precision. | 1. Attach the shaft of stepper motor to the knob and observe whether it can still move at 2 steps per second. | Yes |
| 2. The motor can stop almost within 1.5 seconds when stopping instruction is given. This requirement is very important, since it will determine whether the protection mechanism will work. | 2. Connect the motor drive, stepper motor and signal generator together. Turn on the 5V power supply to run the motor and then disconnect the power supply to stop the stepper motor and record how long it will take the stepper motor to stop moving. | Yes |

## For Power Unit

| Requirement | Verification | Success |
|---|---|---|
| Output voltage of regulator can maintain at 5V to supply power to TTL control circuit and motor. | Connect battery to regulator circuit and use KEYSIGHT Multimeter to measure the output voltage. The output shouldn't fluctuate outside of the range 4.8v to 5.2v. | Yes, but even though the voltage is at 5V, the circuit gets overheated very fast. Therefore, it is subject to improvement. |

# Appendix B Control circuit diagram