3D System-On-Package (SoP) Signal Generator to Control MEMS Movable Microelectrode Arrays

by

Zikai Tee

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Graduate Supervisory Committee:

Jitendran Muthuswamy, Chair
Jemmy Sutanto
Hongyu Yu

ARIZONA STATE UNIVERSITY

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Abstract

Microelectrodes have been used as the neural interface to record brain's neural activities. Most of these electrodes are fixed positioned. Neural signal normally degrades over time due to the body immune response and brain micromotion that move the neurons away from the microelectrode. MEMS technology under SUMMiT V^{TM} processes has developed miniaturized version of moveable microelectrodes that have the ability to recover the neural signal degradation by searching new cluster of neurons. To move the MEMS microelectrode a combination of four voltage waveforms must be applied to four thermally actuated microactuators. Previous design has used Omnetic^{TM} interconnect to transfer the waveforms from the external signal generators to the MEMS device. Unfortunately, the mechanism to attach and detach the Omnetic^{TM} interconnect introduce mechanical stress into the brain tissue that often caused raptures in the blood vessel.

The goal of this project is to create an integrated System-On-Package Signal Generator that can be implanted on the brain of a rodent. A wireless system and a microcontroller are integrated together with the signal generators. The integrated system can be used to generate a series of voltage waveforms that can be customized to drive an array of MEMS movable microelectrodes when a triggered signal is received wirelessly. 3D stacking technique has been used to develop this Integrated System. 3D stacks lead to several favorable factors, such as (a) reduction in the power consumption of the system, (b) reduction in the overall form-factor of the package, and (c) significant reduction the weight of the package.

There are a few challenges that must be overcome in this project, such as a commercially available microcontroller normally have an output voltage of 3.3 V to 5.5 V; however, a voltage of 7 - 8V is required to move the MEMS movable microelectrodes.

To acquire higher density neural recording, more number of microelectrodes are needed. In this project, SoP Signal Generator is design to drive independently 3 moveable microelectrodes. Therefore, 12 voltage waveform are required. . However, the use of 12 signal generators is not a workable option since the system will be significantly large. This brings us to the other challenge, the limiting size of the rodent brain. Due to this factor, the SoP Signal Generator has to be deisgned to be able to fit without causing much pressure to the rodent's brain.

For the first challenge, which is the limited output voltage of 3.3V on the microcontroller, the RC555 timers are used as an amplifier in addition to generating the signals. Demultiplexers have been for the next challenge, which is the need of 24 waveforms to drive 3 electrodes. For each waveform, 1 demultiplexer is used, making a total of 4 demultiplexers used in the entire system, which is a significant improvement from using 12 signal generators. The last challenge can be approached using 3D system stacking technique as mentioned above.

The research aims of this project can be described as follows:

(1) the testing and realization of the system part, and the designing of the system in a PCB level,

(2) implementing and testing the SoP Signal Generator with the MEMS movable microelectrodes,

The final outcome of this project can be used not only for neural applications, but also for more general applications that requires customized signal generations and wireless data transmission.

TABLE OF CONTENTS

Page

CHAPTER

CHAPTER Page

APPENDIX

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER 1

INTRODUCTION

Neural recordings of action potentials in animals such as rats and primates provide unique insights into the neural control of behavior [1]. Microelectrodes have been used as the neural interface to record brain's neural activities for a very long time because of their spatial and temporal resolution. Neural recordings taken from freely behaving animals with chronically implanted microelectrodes have played a major role in the understanding of neuronal activity at the population level [2]. Most of these electrodes are fixed in position. Neural signal normally degrades over time due to the body immune response and brain micromotion that move the neurons away from the microelectrode. However, current microelectrode technologies are not very consistent in their performance and are unreliable in long-term experiments [3]. Therefore, to ensure reliable long-term experiments, a few moveable electrodes have been developed. Movable microelectrode technology is desirable because the electrodes can be repositioned at the loss of signal. Commercially available electrode drives, including those from Thomas Recording [4][5], Alpha-Omega Engineering [6], and Nan Instruments, allow several microelectrodes to be positioned independently on a daily basis, although the head fixation is usually required to stabilize recordings and the range of movement tasks that can be studied with this method is limited [1]. Furthermore, electrodes must be removed at the end of each recording session. This makes it unsuitable for chronic applications where neural recordings of processes that consolidate over days like learning and plasticity cannot be recorded. One such electrode is the hand-controlled movable microdrive. This microdrive uses various kinds of manually adjustable microelectrodes, which rely on miniature screws or threaded rods to advance electrodes [7]. However, it places severe physical stress on the animal during its manipulation, and this stress leads to alertness in the mice and low efficiency in obtaining neural signals from the animal [8].

MEMS technology under SUMMiT V^{TM} processes has enabled the development of miniaturized version of moveable microelectrodes that have the ability to recover the degraded neural signals by searching for active neural interfaces. The MEMS microelectrode array developed in the laboratory has undergone several design iterations and testing in long term experiments [3]. A more detailed description of the latest generation of MEMS movable microelectrode has been given elsewhere [3]. To move the MEMS microelectrode a combination of four voltage waveforms must be applied to four thermally actuated microactuators. Previous design has used Omnetics^{TM} interconnect [3] to transfer the waveforms from the external signal generators to the MEMS device. Unfortunately, the mechanism to attach and detach the Omnetics^{TM} interconnect introduce mechanical stress into the brain tissue. Failure mechanisms that were observed include the formation of debris after the drying of fluids, mounting failures and Omnetics^{TM} interconnect malfunctioning, and broken springs [3]. Most of it was mounting failures which might be attributed to the mechanical stresses caused due to connection and disconnection of the Omnetics^{TM} interconnects. The stress causes a wound-healing response that eventually causes the device to be rejected out of the brain [3]. Hence a more robust package with a built-in signal generator to make this system fully implantable and controllable is needed.

The built-in wireless signal generator allows the possibility of MEMS to become a fully implantable system. By designing a wireless signal generation system, it removes the need to connect and disconnect the Omnetics^{TM} interconnects. This reduces the chances that mounting failures will happen due to mechanical stress. The data required to actuate the electrodes can be sent using wireless. A closed loop control can also be developed with this system. When the electrodes starts detecting less data, the closed loop system can be programmed to send the required signals to actuate the electrodes, and thus, making the system fully automatic. Since the signal generation system is built-in and wireless controlled, it eliminates the need of long daggling wires for the transfer of data. This allows the animal to behave freely without the restriction of connected wirings. Also, as we scale up to high density electrodes, wired signal interfaces would pose as a major problem. Therefore, a signal generation and multiplexing system is required for controlling the movement of the electrodes.

CHAPTER 2

ACTUATION OF MOVABLE ELECTRODES USING WIRELESS SIGNAL GENERATORS

The goal of this project is to create an integrated Signal Generator that can be implanted on the brain of a rodent. A wireless system and a microcontroller are integrated together with the signal generators. The integrated system can be used to generate a series of voltage waveforms that can be customized to drive an array of MEMS movable microelectrodes when a triggered signal is received wirelessly. 3D stacking technique has been used to develop this Integrated System. 3D stacks lead to several favorable factors, such as (a) reduction in the power consumption of the system, (b) reduction in the overall form-factor of the package, and (c) significant reduction the weight of the package. Hence a 3D System-On-Package (SoP) approach was adopted to package the signal generation circuitry.

2.1. General Considerations

2.1.1. Overall Size

To acquire higher density neural recording, more number of microelectrodes are needed. With the increase number of microelectrodes, more waveforms will be needed to actuate the microelectrodes. However, due to the limiting factor of the rodent's brain, the use of more signal generators is not a workable option since the system will be significantly large.

2.1.2. Power Consumption

There is internal power loss in the system, which affects the output of the system. To reduce power loss, the total internal resistance lost through connections must be reduced, which in turn increases current flow and power efficiency.

2.1.3. Animal Behavior

Since the movable microelectrodes will be implanted on a rodent brain, the behavior of the rodent needs to be taken into consideration. When awake, the rodent will move around. Tethered connections would hinder the natural behavior of the animal. Therefore, to eliminate the use of wires, a wireless signal generator is needed.

2.2. Challenges and Approaches

The major challenges that must be overcome in this project are described as follows.

1. Commercially available microcontrollers normally have an output voltage of 3.3 V to 5.5 V; however, a voltage of 7 - 8V is required to move the MEMS movable microelectrodes.

Approach: For the first challenge, which is the limited output voltage of 3.3V on the microcontroller, the RC555 timers are used as a modulating amplifier for the signals.

2. To acquire higher density neural recording, more number of microelectrodes are needed. In this project, SoP Signal Generator is designed to drive independently 3 moveable microelectrodes. Therefore, 12 voltage waveforms are required. . However, the use of 12 signal generators is not a workable option since the system will be significantly large.

Approach: Demultiplexers have been used, For each waveform, 1 demultiplexer is used, making a total of 4 demultiplexers used in the entire system, which is a significant improvement from using 12 signal generators.

3. This brings us to the other challenge, the necessity of a miniaturized package for implantable applications. Due to this factor, the SoP Signal Generator has to be designed to have a small form factor so that the system can be mounted on the animal.

Approach: The last challenge can be approached using 3D system stacking technique as mentioned above.

2.3. Overview of Implemented Wireless Signal Generators Used for Actuation

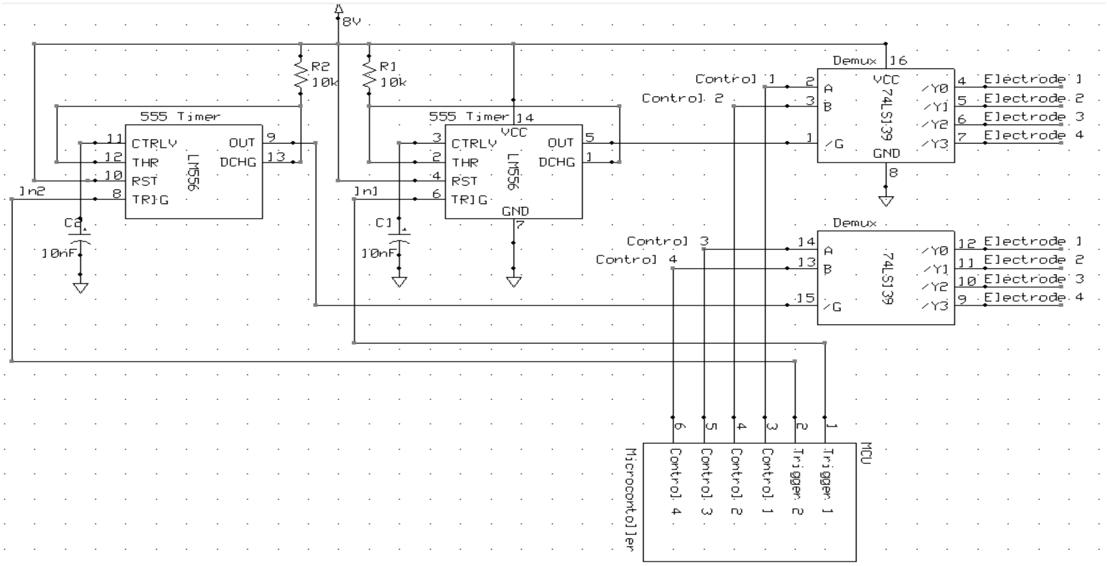


Figure 1: Schematic of the Routing of the Microcontroller, 555 Timers, and the Demultiplexers

The microcontroller (bottom of figure) sends the trigger waveforms to the RC555 timers (top left of figure), the RC555 timers then modulate the waveforms to the correct voltage and sends the modulated waveforms to the demultiplexers (top right of figure). The microcontroller also sends the control signals to the demultiplexers and the demultiplexers choose which electrodes the waveforms go to.

CHAPTER 3

INTEGRATED SYSTEM TO ACTUATE MEMS MOVABLE ELECTRODES

3.1. Receiving Triggers through Bluetooth Device

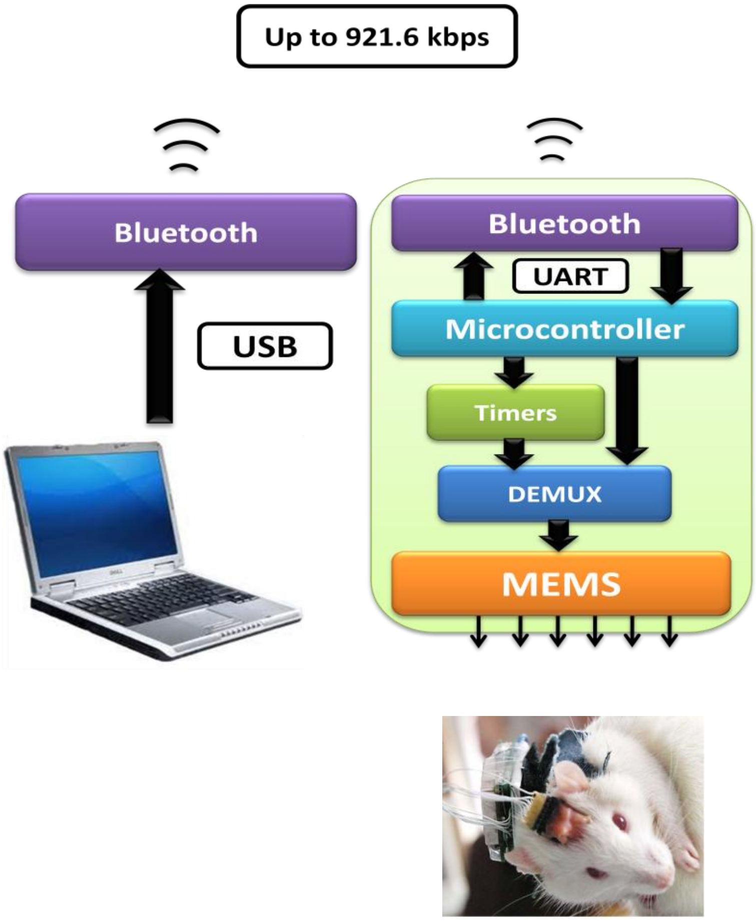


Figure 2: Pathway of Trigger Signal from an External Computer

A single trigger is sent from the computer or laptop to the Bluetooth (right) which is connected through the USB port. The Bluetooth then sends the trigger signals to the Bluetooth receiver which is connected to a microcontroller on the System-On-Package. The microcontroller is programmed to generate a corresponding set of waveforms on receiving a specific trigger signal. The amplitude of these waveforms is at 3.3V. The Bluetooth can send and receive data at up to 921.6 kilo bytes per second.

3.2. Waveform Signal Generation Using Microcontroller and RC555 Timers

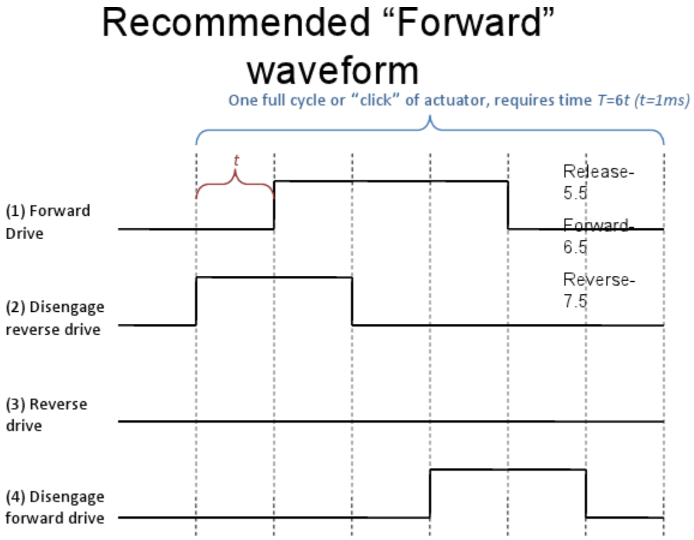


Figure 3: Waveforms Used to Drive the Electrode Forward [9]

To actuate the electrode forward, which is the movement of the electrode out of the MEMS movable electrodes, the above set of waveforms are used. The forward drive is delayed by 1 time period during trigger and then pulled up to 7.5V for 3 time periods and is pulled down. The disengage reverse drive is pulled up to 6.5V immediately after trigger and is pulled down after 2 time periods. The reverse drive stays low throughout the cycle since it is not needed to move the electrode forward. The disengage forward drive is delayed by 4 time periods during trigger and then pulled up to 6.5V for 2 time periods and is pulled down. Only the forward drive, the disengage reverse drive, and the disengage forward drive are needed to actuate the electrode forward.

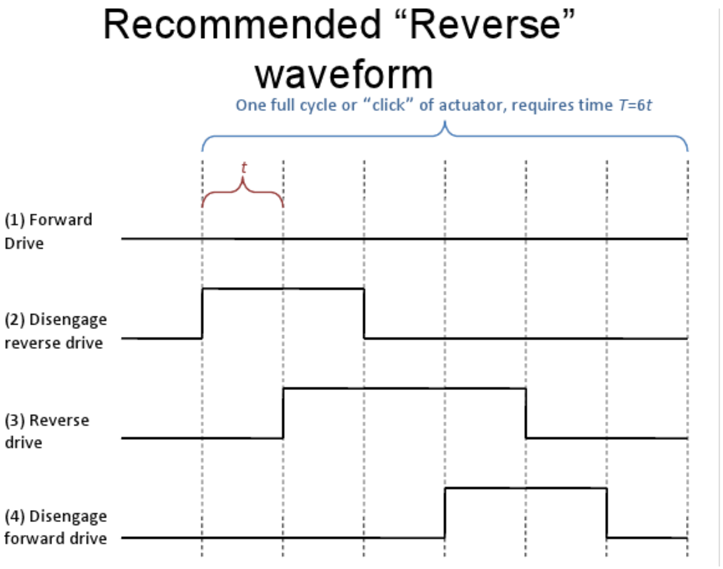


Figure 4: Waveforms Used to Drive the Electrode Backwards [9]

To actuate the electrode backwards, which is the movement of the electrodes backwards into the MEMS movable electrodes, the above waveforms are used. The reverse drive is delayed by 1 time period during trigger and then pulled up to 7.5V for 3 time periods and is pulled down. The disengage reverse drive is pulled up to 6.5V immediately after trigger and is pulled down after 2 time periods. The reverse drive stays low throughout the cycle since it is not needed to move the electrode forward. The disengage forward drive is delayed by 4 time periods during trigger and then pulled up to 6.5V for 2 time periods and is pulled down. Only the reverse drive, the disengage reverse drive, and the disengage forward drive are needed to actuate the electrode forward.

A time period is value of 1 RC, which is the resistance multiplying by the capacitance. A cycle is 6 time periods. Each cycle actuates the electrode once. The waveforms for actuating the electrodes forward and backwards are basically the same, except a waveform is needed on the forward drive to actuate the electrode forward, and a waveform is needed on the reverse drive to actuate the electrode backwards.

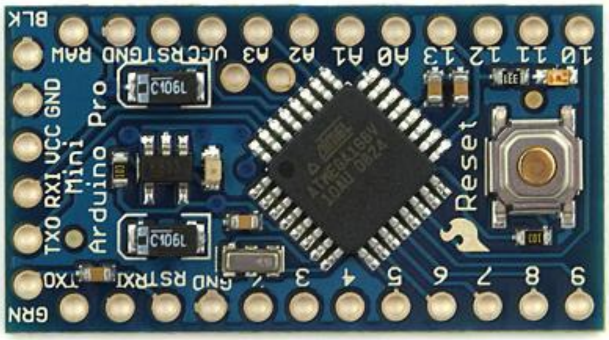


Figure 5: Micrograph showing an Arduino Pro Mini Microcontroller [9]

The microcontroller that has been used for this project is the Arduino Pro Mini. It has a 3.3V output and a 150mA output current. A 3.3V supply voltage is needed to power the microcontroller. It has an area of 0.7 by 1.3 inch and weights less than 2 grams. This microcontroller is suitable for this project due to its small size. However, it does not have sufficient power to drive the electrodes since it only has an output voltage of 3.3V. Therefore, RC555 timer is needed to modulate the output. The Arduino Pro Mini has a programming software of its own. The code to operate it is as follows is given in the appendix. The different triggers and the corresponding set of waveforms generated are shown in table 1.

	Electrode	Forward Drive (1)	Disengage Reverse Drive (2)	Reverse Drive (3)	Disengage Forward Drive (4)	Direction
A	1	H	H	L	H	Forward
B	1	L	H	H	H	Reverse
C	2	H	H	L	H	Forward
D	2	L	H	H	H	Reverse
E	3	H	H	L	H	Forward
F	3	L	H	H	H	Reverse

Table 1: Truth Table of Triggering Signals for the Microcontroller

When trigger “a” is sent, the waveforms for driving electrode 1 forward are generated in the microcontroller. When trigger “b” is sent, the waveforms for driving electrode 1 backwards are generated in the microcontroller. When trigger “c” is sent, the waveforms for driving electrode 2 forward are generated in the microcontroller. When trigger “d” is sent, the waveforms for driving electrode 2 backwards are generated in the microcontroller. When trigger “e” is sent, the waveforms for driving electrode 3 forward are generated in the microcontroller. When trigger “f” is sent, the waveforms for driving electrode 3 backwards are generated in the microcontroller.

3.3. Distribution of Demultiplexer

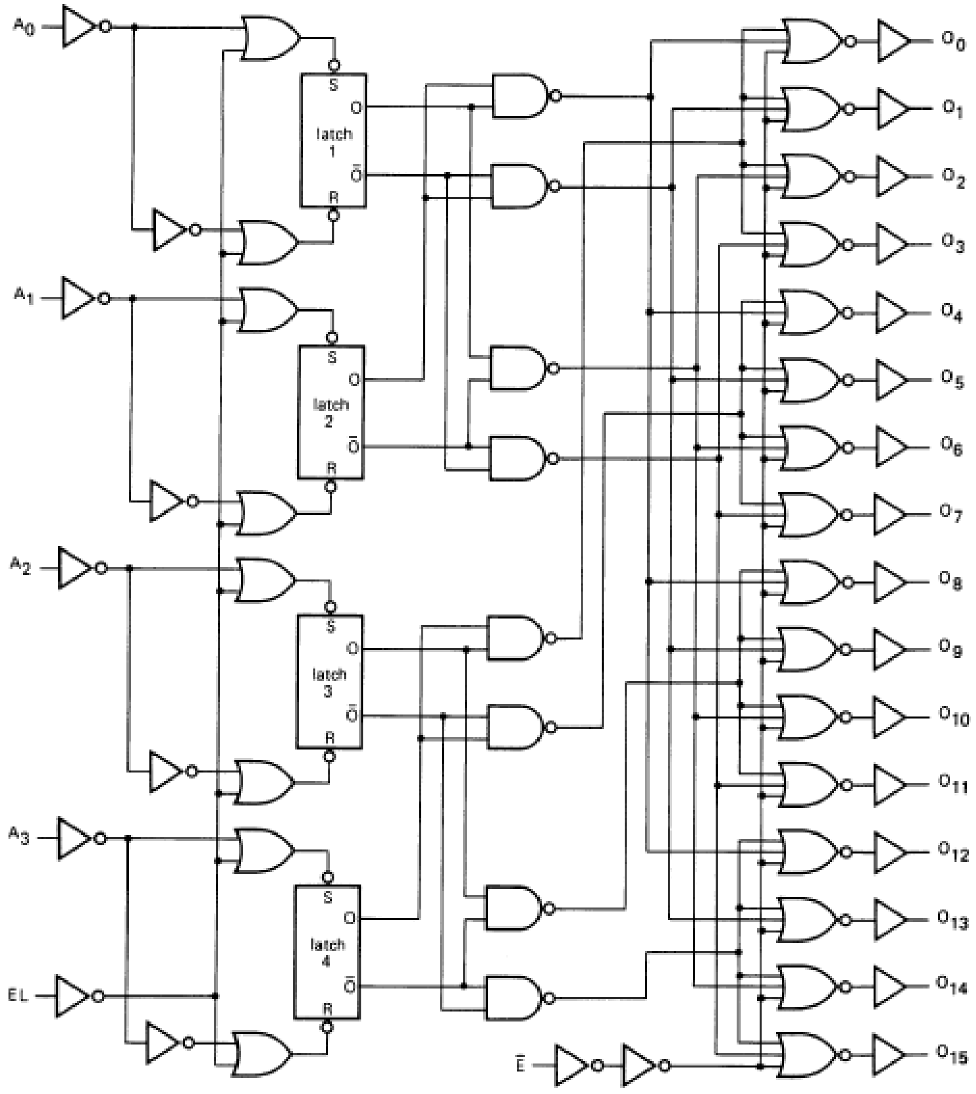


Figure 6: Layout of the 1-to-16 Demultiplexer [11]

	Electrode	Selection Signal 1	Selection Signal 2	Selection Signal 3	Selection Signal 4
a	1	0	0	0	0
b	1	0	0	0	0
c	2	0	0	0	1
d	2	0	0	0	1
e	3	0	0	1	0
f	3	0	0	1	0

Table 2: Truth Table of the 1-to-16 Demultiplexer for the Selection of Three Electrodes since the MEMS Device has Three Electrodes

The purpose of the demultiplexer is to select which electrode the waveform goes to. This particular demultiplexer can select one out of sixteen outputs for the waveform to go to. A selection signal is given together with the triggering waveforms from the microcontroller. The selection signals are then passed through another 555 timer which modulates it to the correct voltage to operate the demultiplexer what is the required voltage? The selection signals are then passed together with the one of the four generated waveforms to a singledemultiplexer. The demultiplexer then, after processing the selection signals, selects the correct electrode the waveforms go to. The selection signals are shown in table 2. So we would need four demultiplexers, for sending all of the four waveforms to actuate the appropriate electrode.

3.4. Integrating with MEMS Packaged Device

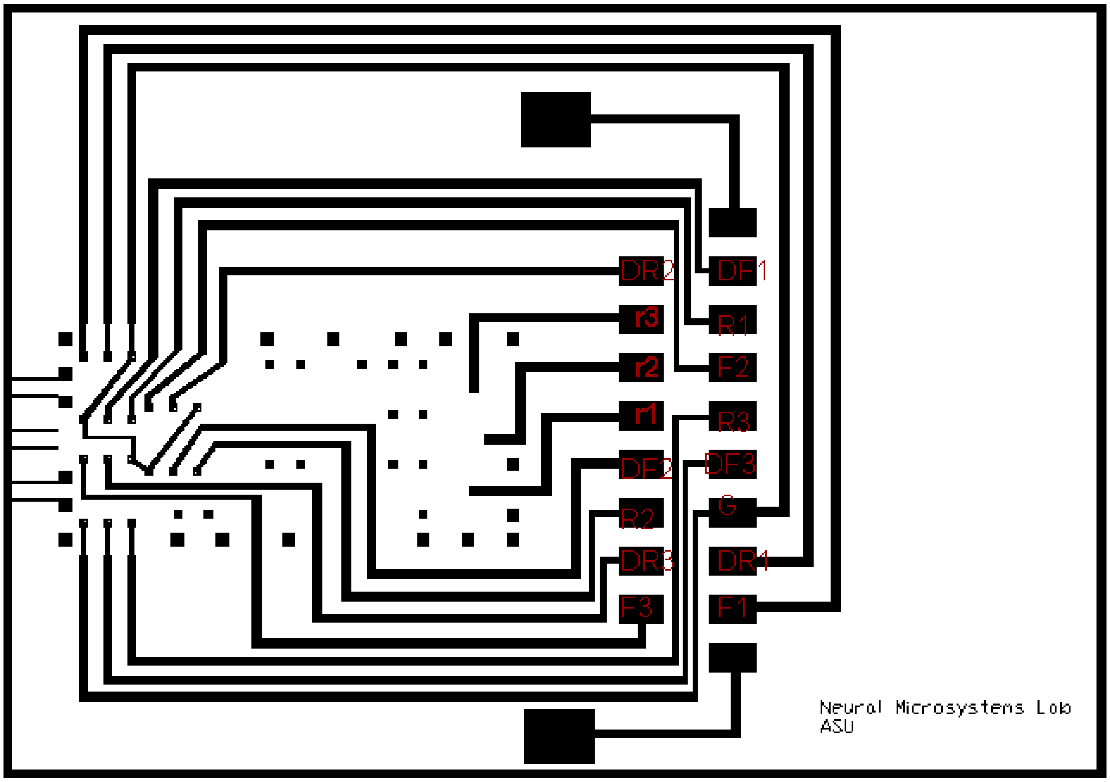


Figure 7: Micrograph of the AUTOCAD mask showing the outing of the leads in the first level interconnect in a flip chip packaged MEMS Device with Female Header [12]

MEMS device is flip chip packaged with glass interconnect [12]. Each bond pad in the device is connected by silver epoxy bumps to gold bondpads on the first level interconnect[12]. The gold leads then connect to the bondpads for Omnetics™ connector [12].

Each of the MEMS Movable Electrodes has three electrodes. In figure 6, on the first row (left row), the pads, from top to bottom, are for the following functions: disengage reverse drive waveform for electrode 2, neural signal output 3, neural signal output 2, neural signal output 1, disengage forward drive waveform for electrode 2, reverse drive waveform for electrode 2, disengage reverse drive waveform for electrode 3, forward drive waveform for electrode 3. On the second row (right row), the pads, from top to bottom, are for the following functions: not used, disengage forward drive waveform for electrode 1, reverse drive waveform for electrode 1, forward drive waveform for electrode 2, reverse drive waveform for electrode 3, disengage forward drive waveform for electrode 3, ground, disengage reverse drive waveform for electrode 1, forward drive waveform for electrode 1, not used. The female header is connected to the male header which is packaged together with the system.

CHAPTER 4

DESIGN OF INTEGRATED SYSTEM ON 2D PCB LEVEL FOR AREA COMPARISON

4.1. Design of 555 Timers

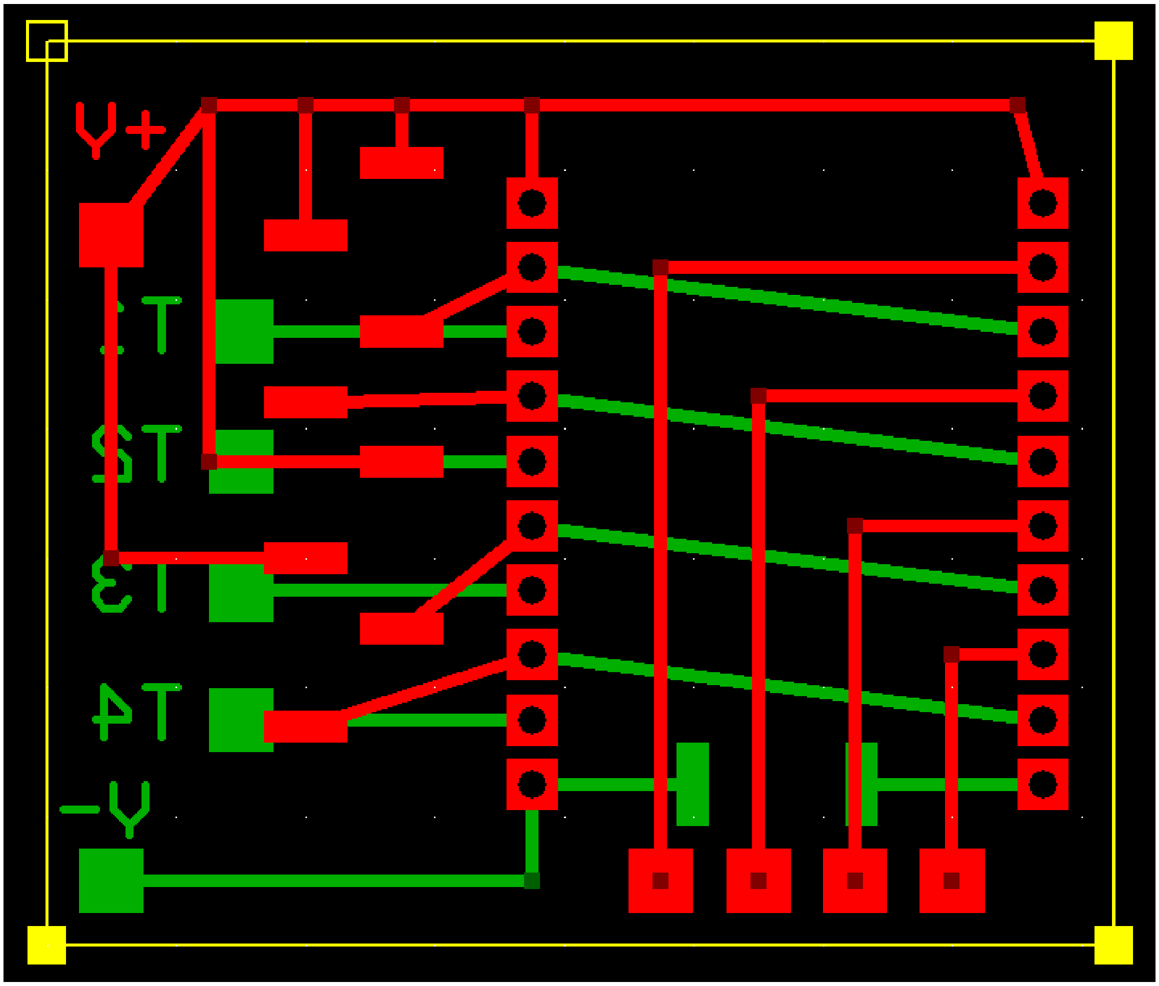


Figure 8: Layout of RC555 Timer with Resistance and Capacitance on 2D Design

The quad 555 timer is used for this design. The layout is done in the PCB software, ExpressPCB, with the red representing the top layer, and the green representing the bottom layer. On the top layer, on the far left is the voltage source input, which is connected to reset and V+ pins of the 555 timer, as well at one end of the resistors. The resistors are connected to the voltage source input, the discharge pins and the threshold pins of the 555 timer. The outputs are placed on square pads on the lower right of the layout, which is connected to the outputs of the 555 timer. On the bottom layer, the four input waveforms, T1, T2, T3, T4, are connected to the inputs of the 555 timer. The discharge and threshold pins are linked together by lines. The ground input is connected to the V- pin of the 555 timer, which is also connected to the negative end of the capacitor. The positive end of the capacitor is connected to the control pin of the 555 timer. The inputs to the 555timer are the generated waveforms from the microcontroller which is at 3.3V. The outputs of the 555 timer are the modulated and amplified waveforms that are generated by the microcontroller which is at 7V to 8V.

4.2. Design of Demultiplexer

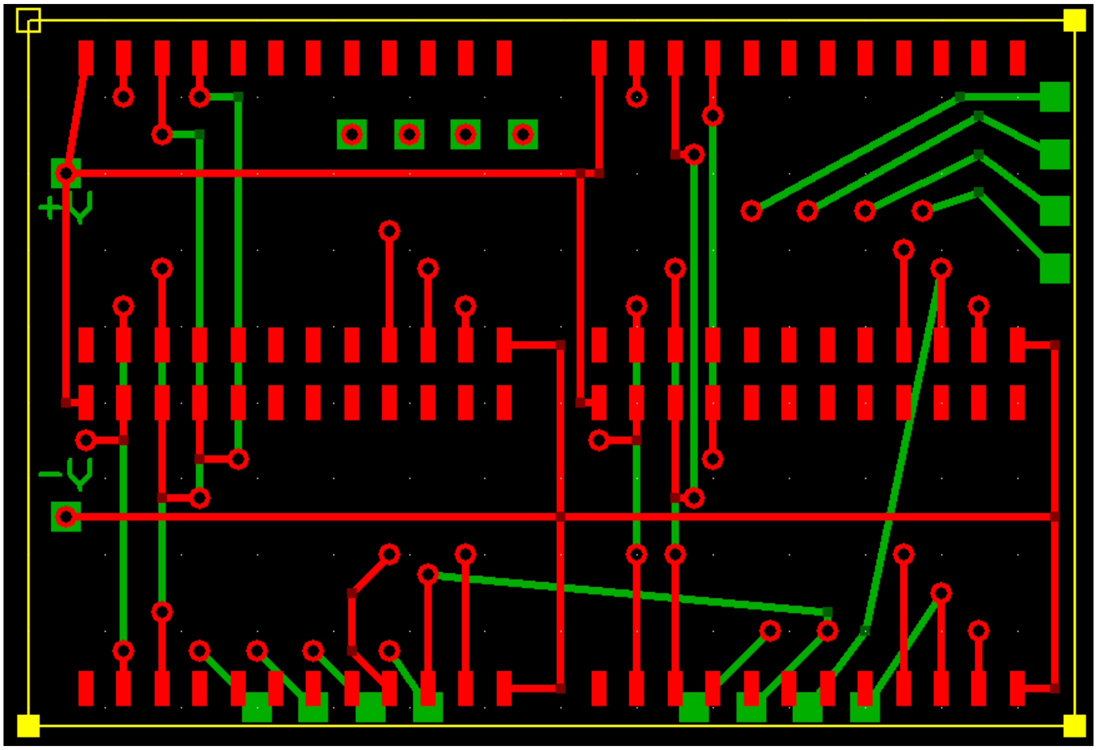


Figure 9: Top and Bottom Layer of 1-to-16 Demultiplexer Layout

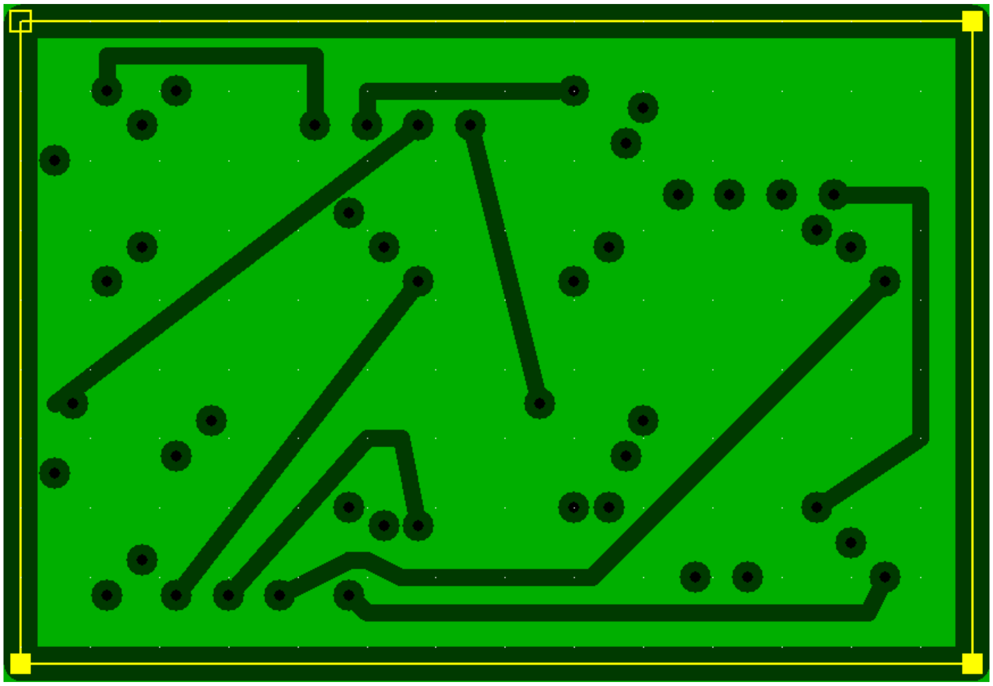


Figure 10: Inner Ground Layer of Demultiplexer Layout

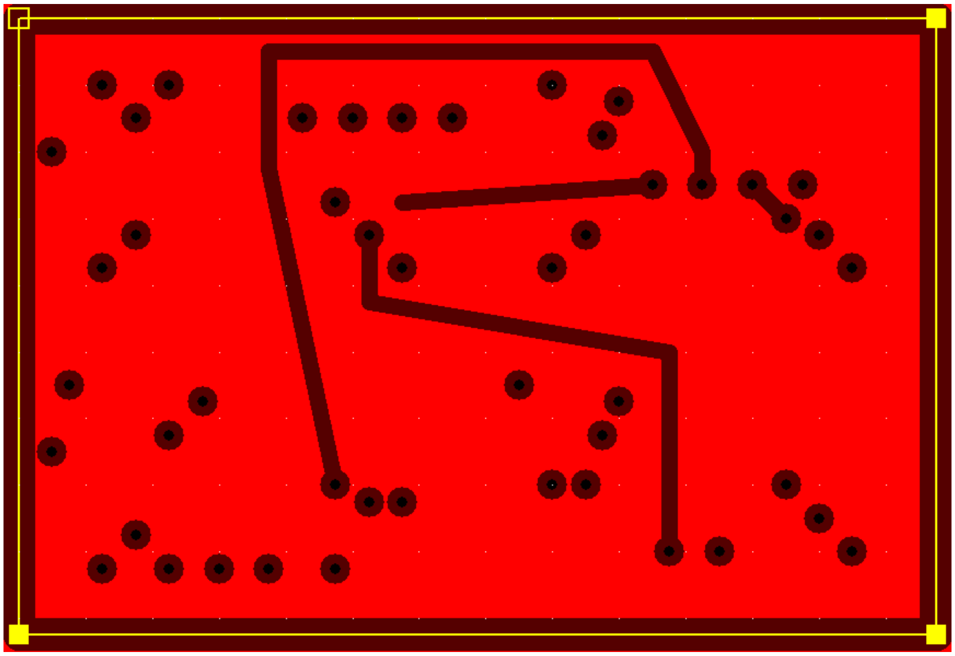


Figure 11: Inner Power Layer of Demultiplexer Layout

The 1-to-16 demultiplexer is used for this project. Since there are four waveforms, 4 demultiplexers are needed in total. The reason for choosing a 1-to-16 demultiplexer instead of a 1-to-4 demultiplexer is so that the future, by modifying this design, more MEMS movable electrode devices can be added while still using the same system. Figure 9, figure 10, and figure 11 shows the design of the demultiplexers. On the top layer, the four demultiplexers are laid on the four corners of the entire layout. The power source is connected to the V+ pad on the upper left of the layout which is then connected to each of the V+ pins of each individual demultiplexer. The ground is connected to the V- pad on lower left of the layout which is then connected to the V- pins of each demultiplexer. Each selection signal pins are connected to its counterpart on all four demultiplexers. On the bottom layer, on the upper middle of the layout, there are 4 pads with through holes, which are for the input waveforms for the demultiplexer. On the upper right, lower left, and lower right of the layout, there are three sets of 4 pads. These pads are the pads for the outputs of the demultiplexers. The inner power and inner ground layers are used to connect the output pins of the demultiplexers to their respective outputs on the layout. There are two sets of inputs for the demultiplexers. The first set is the waveforms generated by the microcontroller and modulated by the 555 timers. Each waveform is an input for each demultiplexer respectively. The second set of inputs is the 4 selection signals, which is shared between all demultiplexers. The outputs will be the 4 modulated waveforms, which, depending on the selection signal, will go to the pads on the upper right, the pads on the lower left, or the pads on the lower right.

4.3. The Full Design

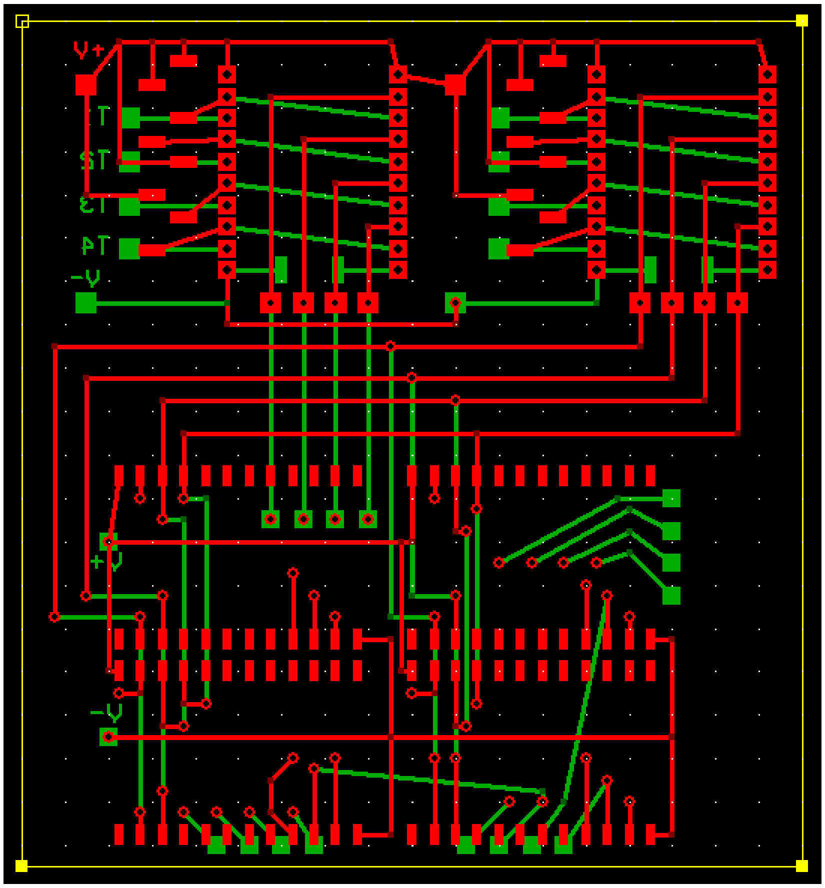


Figure 12: The Full Layout with the 555 Timers and the Demultiplexers

The full layout, which combines the 555 timers and the demultiplexers, is shown in figure 12. The 555 timers are placed on the top side of the layout, and the demultiplexers are places on the bottom side of the layout. The power source and ground is shared by both. The inputs of the 555 timers are connected to the outputs of the microcontroller, which provides both the set of generated waveforms and the selection signals. The set of generated waveforms is connected to the 555 timer on the upper left of the layout. The outputs of this 555 timer are connected to the waveform inputs of the demultiplexer, which is in the middle of the layout. The set of selection signals is connected to the upper right of the layout. The outputs of this 555 timer are connected to the selection inputs on all four of the demultiplexers since they share the same selection signals. The layout is 1.8 inch by 1.95 inch and it has 2 layers. The total surface area for this design is 7.02 inches squared.

CHAPTER 5

TAKING INTEGRATED SYSTEM-ON-PACKAGE TO THE NEXT DIMENSION

5.1. Advantages in the Three Dimension Design of the System-On-Package

There are many advantages in designing the system in 3D. First, it reduces the area of the system. By stacking the layers of PCB in the vertical axis instead of just adding it on a 2D level, the area of the system is largely reduced. Second, the internal resistance is also reduces due to the simplifying of the complex routings in 2D design. There are a lesser amount of long routings on the 3D design than the 2D design. Also, doing the design on 3D removes the need of used the inner power and inner ground layers. Third, with the reduction of internal resistance, it also increases power efficiency. The internal resistance of the 2D design is 0.27 milli-Ohms, and the total internal resistance for the 3D design is 0.095 milli-Ohms. However, the reduction in the power efficiency is not significant enough for a small scale design for the MEMS movable electrodes. However, if the design scales up to a thousand times or even ten thousand times, the reduction in the internal resistance will start to affect the system.

5.2. Problems in the Three Dimension Design of the System-On-Package

There are a few problems in moving a 2D system to a 3D system. The first problem in moving the 2D system to a 3D system is the layout of the 555 timers. Due to the huge reduction in area, the 555 timer chip and its corresponding resistors and capacitors required can no longer be placed on the same layout. Therefore, 2 layouts have to be used in order to make a functioning 555 timer. The second problem is the stacking of the 3D system. Since the layers are stacked vertically up, the internal supporting wires of the system must be firm. Also, the exposed internal supporting wires are slightly affected by noise.

5.3. Three Dimension Design of the System-On-Package

5.3.1. 555 Timer

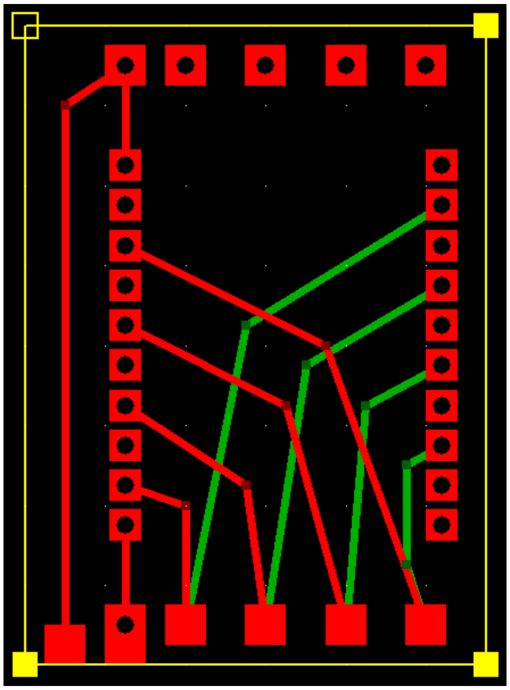


Figure 13: First Layer of the Layout of the 555 Timer for the Generated Waveforms Which Includes the Input, Output Pins, and the 555 Timer Itself.

Shown in figure 13 is the layout for the 555 timer for the generated waveforms of the microcontroller. On the top layer, the power source and the ground are connected to the pads on the two pads on the left most of the lower part of the layout. The power source is connected to the reset pin of the 555 timer. The generated waveforms from the microcontroller are connected to the inputs of the 555 timer through the four pads on the lower right side of the layout. On the upper part of the layout, the 4 pads on the right are through pass that passes the selection signals through to the next layer of the system. On the bottom layer, the outputs of the 555 timer are connected to the output pads, which are arranged in reverse to the input pads.

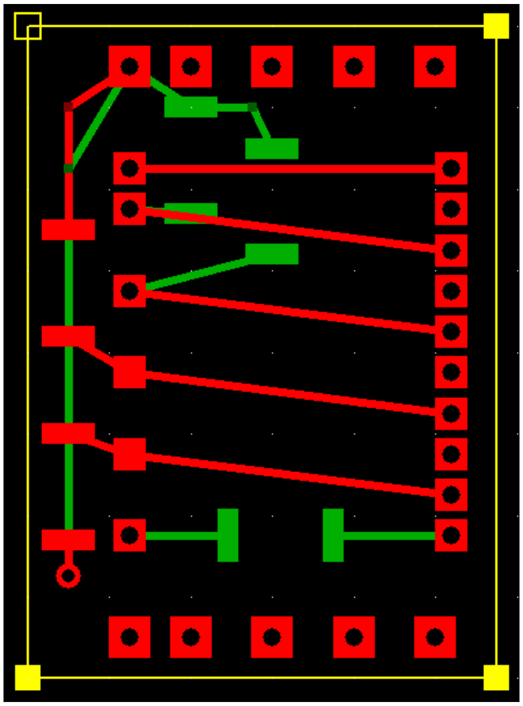


Figure 14: Second Layer of the Layout of the 555 Timer for the Generated Waveforms Which Includes the Resistors and Capacitor.

Figure 14 shows the layout for the resistors and capacitor for the 555 timer for the generated waveforms of the microcontroller. The upper through holes are for passing the power source and the selection signals to the next layer, the lower through holes are for passing the ground and the modulated waveforms to the next layer. The pads in the middle acts as an interface to connect this layer to the previous layer, which has the 555 timer chip mounted. The resistors are connected to the power source and then discharge pins of the 555 timer. The discharge pins are then connected with the threshold pins of the 555 timer. The positive end of the capacitor is connected to the control pin of the 555 timer and the negative end is connected to the ground.

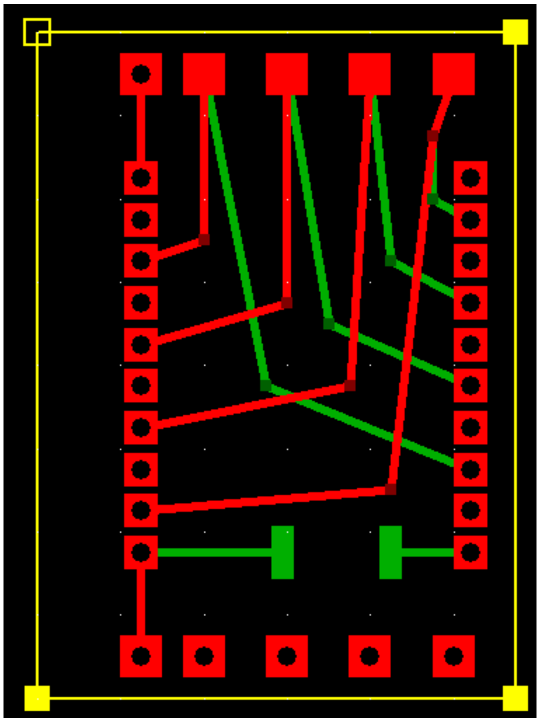


Figure 15: First Layer of the Layout of the 555 Timer for the Selection Signals Which Includes the Input, Output Pins, the Capacitor, and the 555 Timer Itself.

Shown in figure 15 is the layout for the 555 timer for the selection signals of the microcontroller. On the top layer, the power source is connected to the upper left through hole of the layout and the ground is connected to the lower left through hole of the layout. The power source is connected to the reset pin of the 555 timer. The selection signals received from the microcontroller which are passed through the previous layers are connected to the inputs of the 555 timer through the four pads on the upper right side of the layout. On the lower part of the layout, the 4 pads on the right are through pass that passes the modulated waveforms through to the next layer of the system. On the bottom layer, the outputs of the 555 timer are connected to the output pads, which are arranged in reverse to the input pads. The positive end of the capacitor is connected to the control pin of the 555 timer and the negative end is connected to the ground.

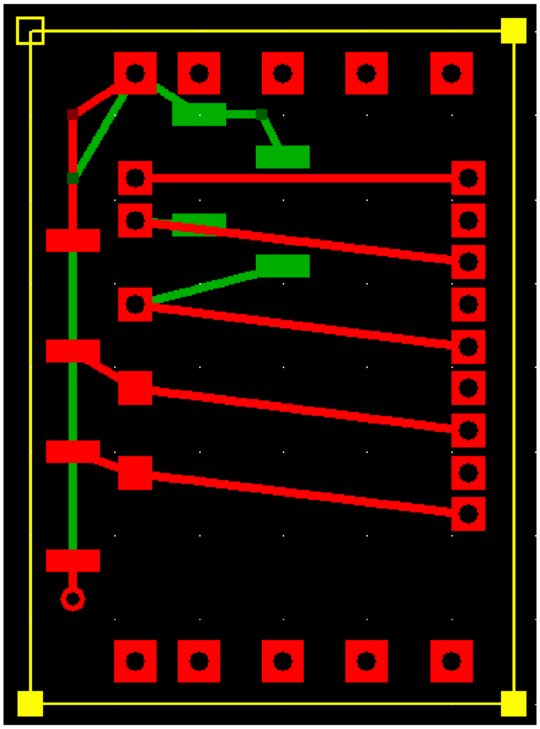


Figure 16: Second Layer of the Layout of the 555 Timer for the Selection Signals Which Includes the Resistors.

Figure 16 shows the layout for the resistors and capacitor for the 555 timer for the selection signals of the microcontroller. The upper through holes are for passing the power source and the selection signals to the next layer, the lower through holes are for passing the ground and the modulated waveforms to the next layer. The pads in the middle acts as an interface to connect this layer to the previous layer, which has the 555 timer chip mounted. The resistors are connected to the power source and then discharge pins of the 555 timer. The discharge pins are then connected with the threshold pins of the 555 timer.

5.3.2. Demultiplexer

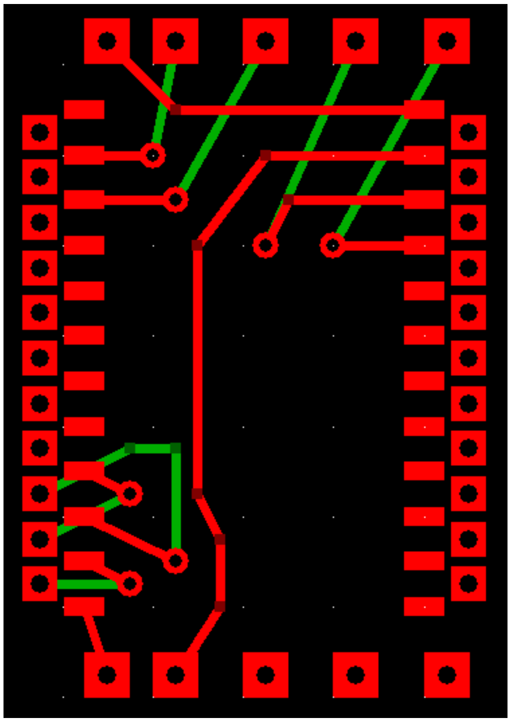


Figure 17: First Layer of the Demultiplexers

Figure 17 shows the layout for the first demultiplexer. On the top layer, the power source is connected to the upper left through hole of the layout and the ground is connected to the lower left through hole of the layout. The power source pad is then connected to the V+ pin of the demultiplexer, and the ground pad is connected to the V- pin. The four selection inputs that are passed down from the previous layers are connected to the A0,A1,A2,A3 pins of the demultiplexer through the four through on the upper right of the layout. The first modulated waveform that is passed down from the previous layers is connected to the EL pin of the demultiplexer through the through hole to the right of the ground through hole. On the bottom layer, the outputs are connected to first, second and third lower left through holes to enable the passing of the waveforms to the final layer of the system. The first through hole is for electrode 1, the second through hole is for electrode 2, and the third through hole is for electrode 3.

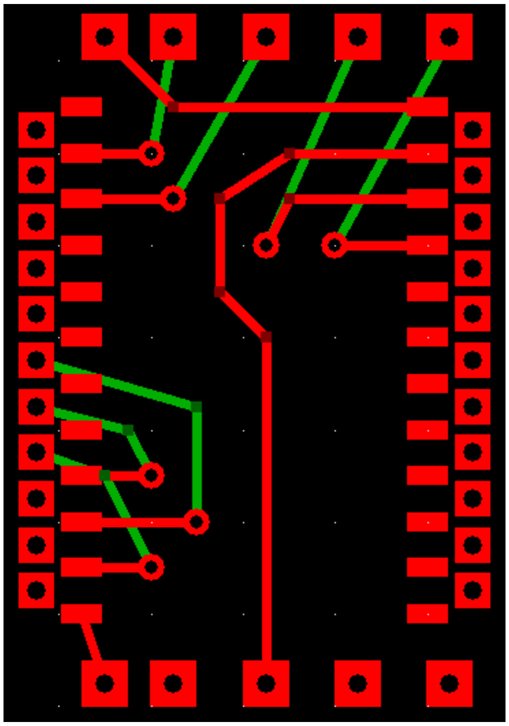


Figure 18: Second Layer of the Demultiplexers

Figure 18 shows the layout for the second demultiplexer. On the top layer, the power source is connected to the upper left through hole of the layout and the ground is connected to the lower left through hole of the layout. The power source pad is then connected to the V+ pin of the demultiplexer, and the ground pad is connected to the V- pin. The four selection inputs that are passed down from the previous layers are connected to the A0,A1,A2,A3 pins of the demultiplexer through the four through on the upper right of the layout. The second modulated waveform that is passed down from the previous layers is connected to the EL pin of the demultiplexer through the second through on the right of the ground through hole. On the bottom layer, the outputs are connected to the fourth, fifth and sixth lower left through holes to enable the passing of the waveforms to the final layer of the system. The fourth through hole is for electrode 1, the fifth through hole is for electrode 2, and the sixth through hole is for electrode 3.

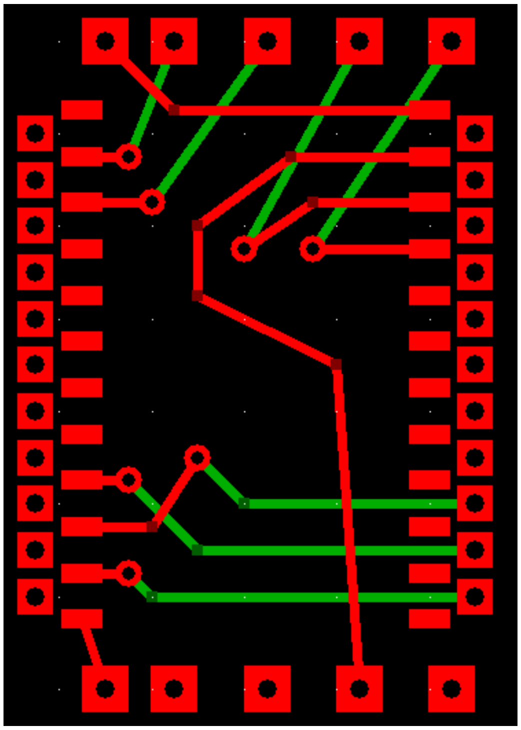


Figure 19: Third Layer of the Demultiplexers

Figure 19 shows the layout for the third demultiplexer. On the top layer, the power source is connected to the upper left through hole of the layout and the ground is connected to the lower left through hole of the layout. The power source pad is then connected to the V+ pin of the demultiplexer, and the ground pad is connected to the V- pin. The four selection inputs that are passed down from the previous layers are connected to the A0,A1,A2,A3 pins of the demultiplexer through the four through on the upper right of the layout. The third modulated waveform that is passed down from the previous layers is connected to the EL pin of the demultiplexer through the third through hole to the right of the ground through hole. On the bottom layer, the outputs are connected to the fourth, fifth and sixth lower right through holes to enable the passing of the waveforms to the final layer of the system. The first through hole is for electrode 1, the second through hole is for electrode 2, and the third through hole is for electrode 3.

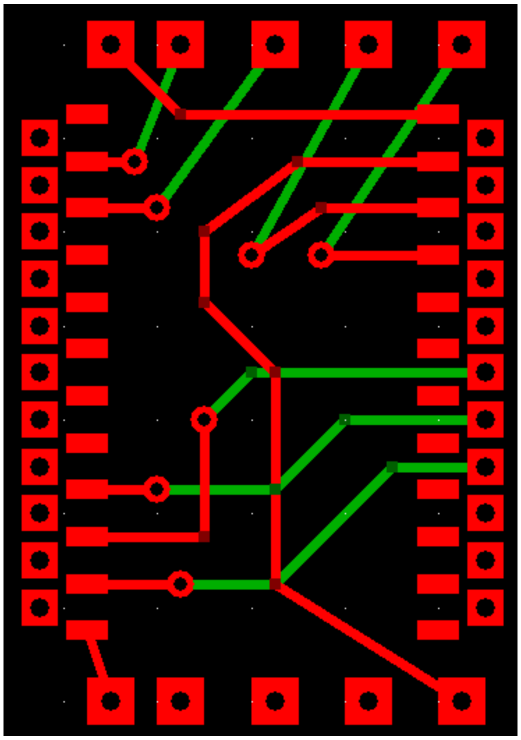


Figure 20: Fourth Layer of the Demultiplexers

Figure 20 shows the layout for the fourth demultiplexer. On the top layer, the power source is connected to the upper left through hole of the layout and the ground is connected to the lower left through hole of the layout. The power source pad is then connected to the V+ pin of the demultiplexer, and the ground pad is connected to the V- pin. The four selection inputs that are passed down from the previous layers are connected to the A0,A1,A2,A3 pins of the demultiplexer through the four through on the upper right of the layout. The fourth modulated waveform that is passed down from the previous layers is connected to the EL pin of the demultiplexer through the fourth through hole to the right of the ground through hole. On the bottom layer, the outputs are connected to the three lower left through holes to enable the passing of the waveforms to the next layer of the system. The fourth through hole is for electrode 1, the fifth through hole is for electrode 2, and the sixth through hole is for electrode 3.

5.3.3. Design of Omnetics^{TM}

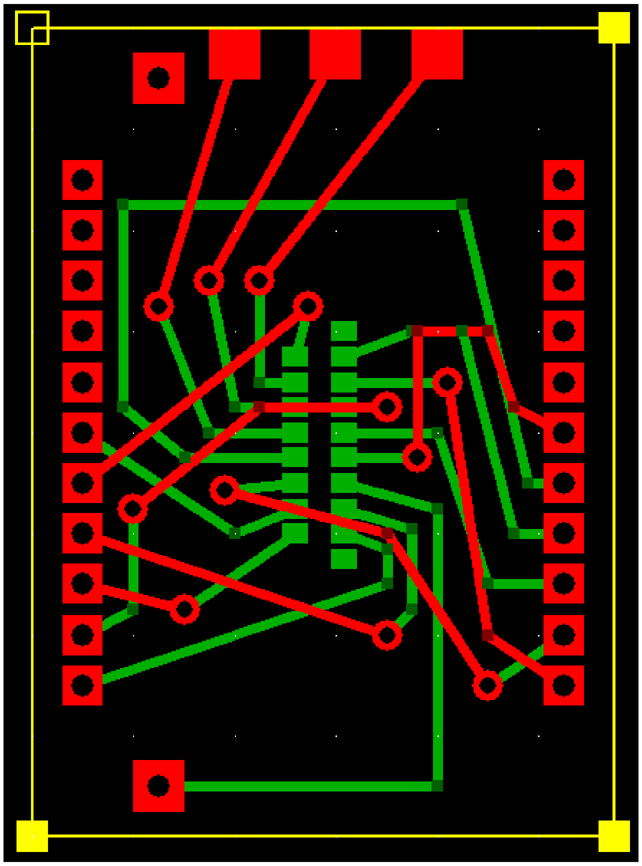


Figure 21: Layer for the Omnetics^{TM} Male Header

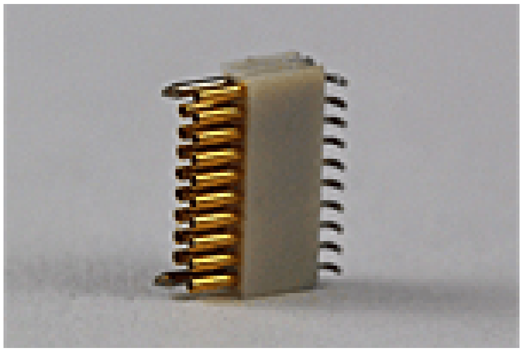


Figure 22: Actual Omnetics^{TM} Male Header [13]

In figure 21, the layout for the Omnetics^{TM} male header is shown. The ground, four waveforms that are routed to electrode 1, electrode 2 and electrode 3 are passed down to the through holes on this layer, which are connected to their corresponding counterparts on the male header. The 3 pads on the upper middle side of the layout are used for the output data of the electrodes. More details on the Omnetics^{TM} can be found in figure 7.

5.4. Implementation

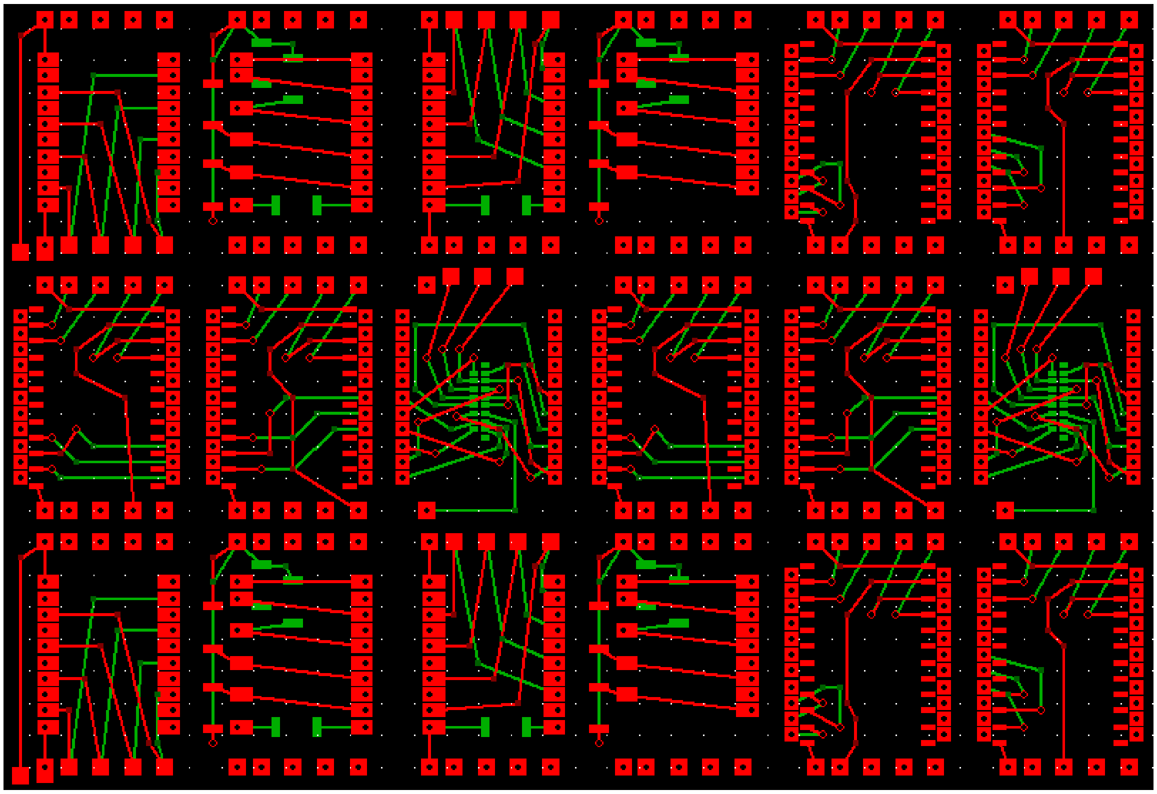


Figure 23: Layout of Two Sets of Entire Signal Generator System

Figure 23 shows the layout of two sets of all the 9 layers of the signal generator excluding the Bluetooth and the microcontroller. This layout is sent for manufacturing and then cut at the factory to reduce the cost of product.

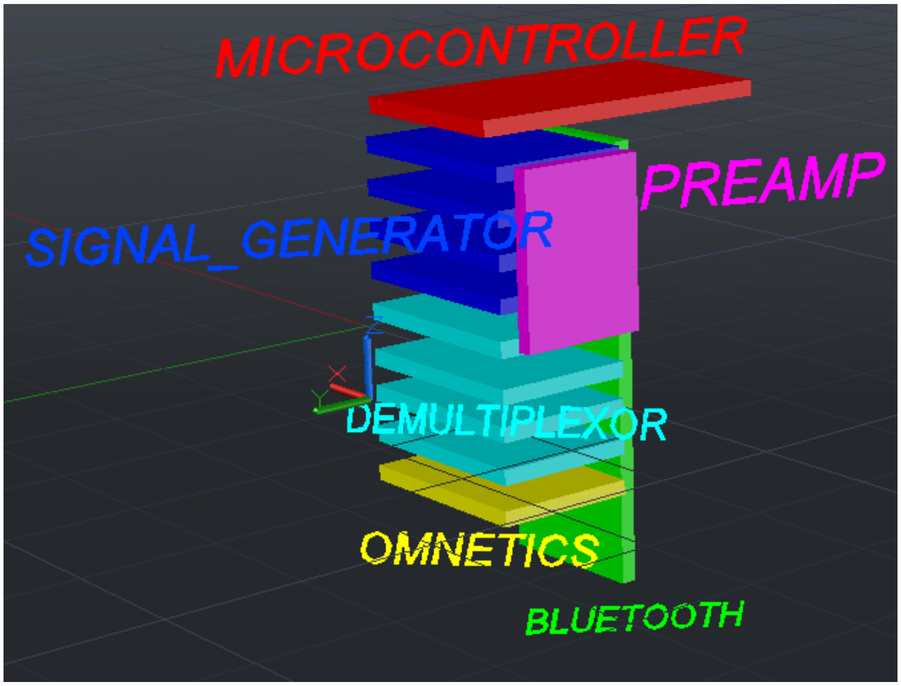


Figure 24: Model of the Packaged Signal Generator Using AutoCAD

Figure 24 shows the expected packaged system of the entire SoP including the microcontroller, the Bluetooth and the preamplifier. The microcontroller is the first on the stack, followed by the 555 timers for both the generated waveforms and the selection signals. The demultiplexer comes after the 555 timers, and the final layer is the Omnetics^{TM}. The Bluetooth is connected on the side to the microcontroller. The preamplifier is used to amplify the neural signals that are detected by the electrodes by a factor of 200 before sending the data to the computer wirelessly.

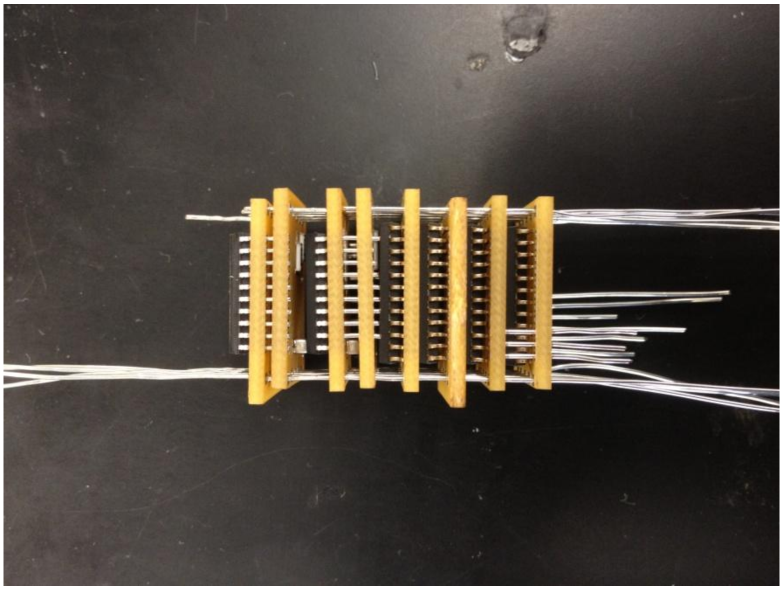


Figure 25: Actual Packaged System without the Microcontroller and Bluetooth

Figure 25 shows the packaged system without the microcontroller and the Bluetooth connected. Each PCB layer is 0.575 inch by 0.8 inch. There are a total of 9 layers. The total surface area is 4.14 inches squared.

	Minimum	Maximum	Average	Units
Voltage Output	6.5	9.5	7	V
Current Output	70	100	72	mA
Standby Current	270	450	300	uA

Table 3: SoP Operation Specifications

Table 3 shows the operation specifications of the SoP. The minimum voltage to operate the system is 6.5V, and the corresponding current output and standby current for this voltage is 70mA and 270 uA respectively. The maximum voltage to operate the system is 9.5V, and the corresponding current output and standby current for this voltage is 100mA and 450uA respectively. The average operating voltage is 7V, and the corresponding current output and standby current for this voltage is 72mA and 300uA respectively.

5.5. Alternate Design

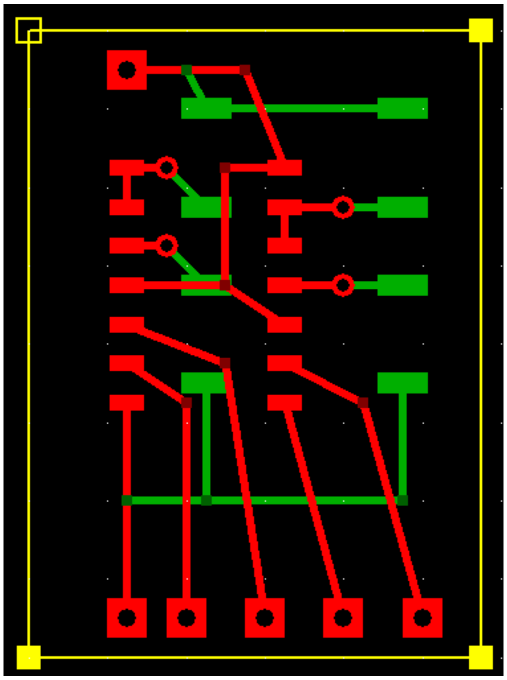


Figure 26: Layout for Dual 555 Timer with Resistors and Capacitors

Figure 26 shows the layout for the dual 555 timer with its resistors and capacitors. On the top layer, the power source is connected to the upper left through hole of the layout and the ground is connected to the lower left through hole of the layout. The power source is connected to the V+ pin of the dual 555 timer and the ground is connected to the V- pin of the dual 555 timer. The resistors are connected to the power source and the discharge pins of the dual 555 timer. The discharge pins are connected to the threshold pins of the dual 555 timer. The positive ends of the capacitors are connected to the control pins of the 555 timer and the negative end is connected to ground.

CHAPTER 6

EXPERIMENTAL RESULTS

To test the SoP, it is connected to the oscilloscope and the results are then taken. The outputs of the SoP is connected to the oscilloscope 2 at a time since there are only 2 inputs to the oscilloscope. After testing and checking the output waveforms, the SoP is then connected to the MEMS Device and a video is recorded for actuating the MEMS movable electrodes.

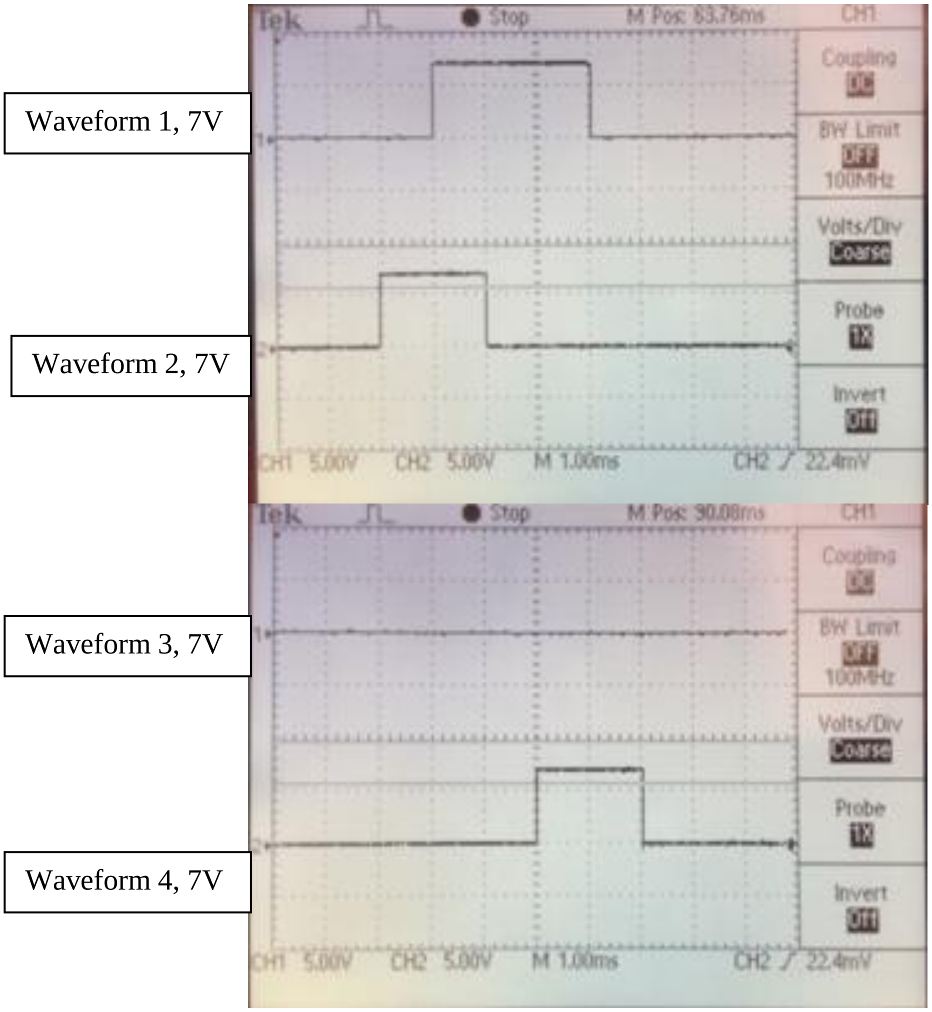
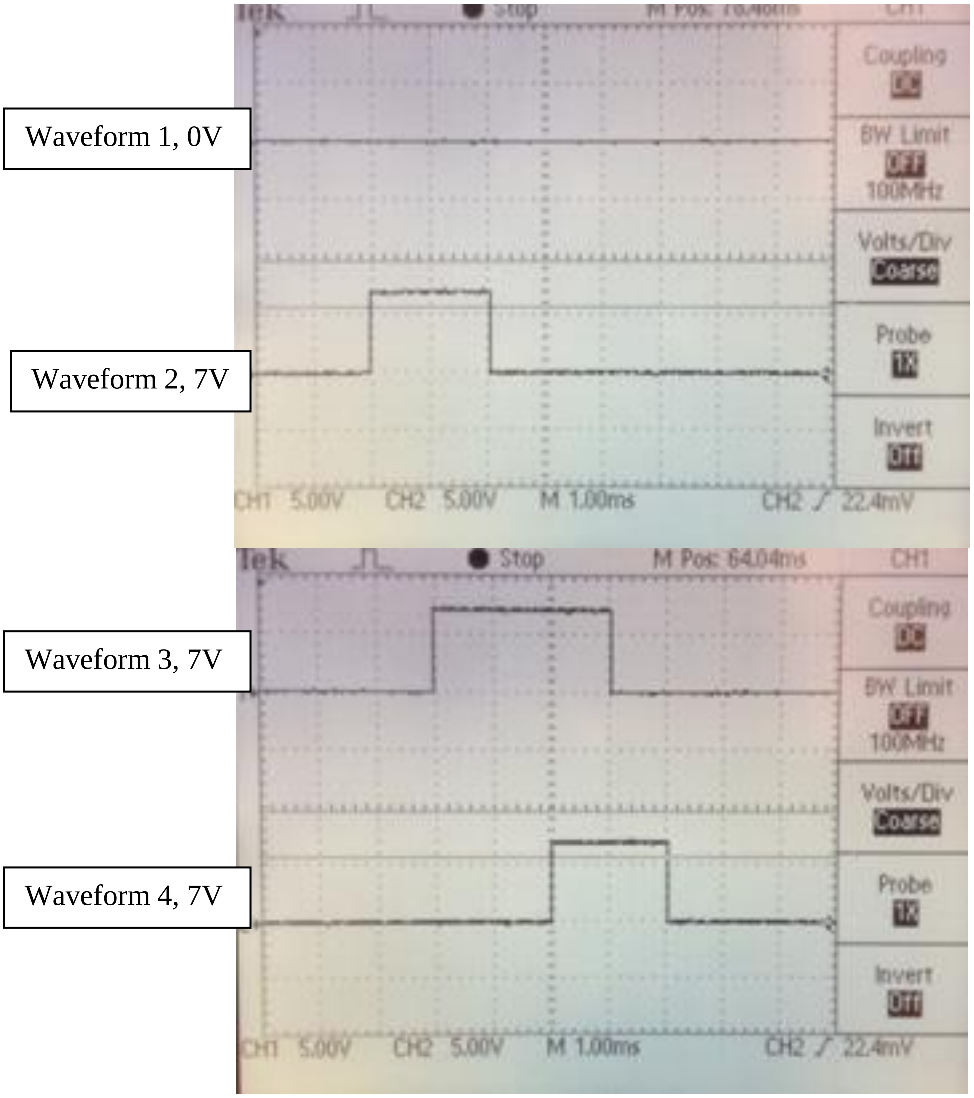


Figure 27: Waveforms for the Forward Drive

Figure 27 shows the waveforms for actuating the electrode forward for electrode 1 using the SoP. Waveform 1 shows the waveform for the forward drive for electrode 1. Waveform 2 shows the waveform for the disengage reverse drive for electrode 1. Waveform 3 shows the waveform for the reverse drive for electrode 1. Waveform 4 shows the disengage forward drive for electrode 1. All 4 waveforms must be working together to actuate the electrode forward. The test results show that it has the correct waveforms and has enough voltage to drive the electrode.



Waveform 1, 0V

Waveform 2, 7V

Waveform 3, 7V

Waveform 4, 7V

Figure 28: Waveforms for the Reverse Drive

Figure 28 shows the waveforms for actuating the electrode backward for electrode 1 using the SoP. Waveform 1 shows the waveform for the forward drive for electrode 1. Waveform 2 shows the waveform for the disengage reverse drive for electrode 1. Waveform 3 shows the waveform for the reverse drive for electrode 1. Waveform 4 shows the disengage forward drive for electrode 1. All 4 waveforms must be working together to actuate the electrode backwards. The test results show that it has the correct waveforms and it has enough voltage to drive the electrode.

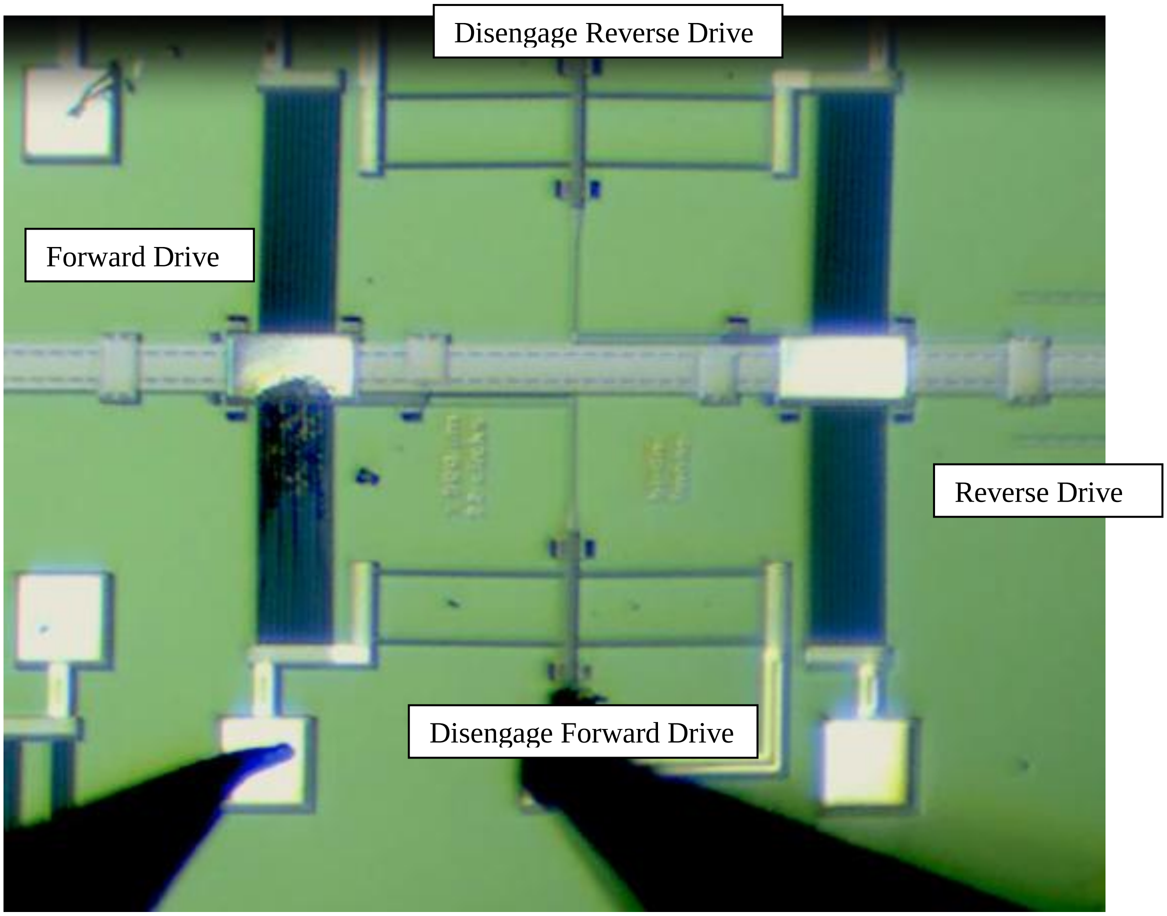


Figure 29: Electrode of MEMS Device at its Natural State

Figure 29 shows the MEMS movable electrode in its natural state. The forward drive is located on the left of the figure. The reverse drive is located on the right of the figure. The disengage forward drive is located on the bottom of the figure. The disengage reverse drive is located on the top of the figure.

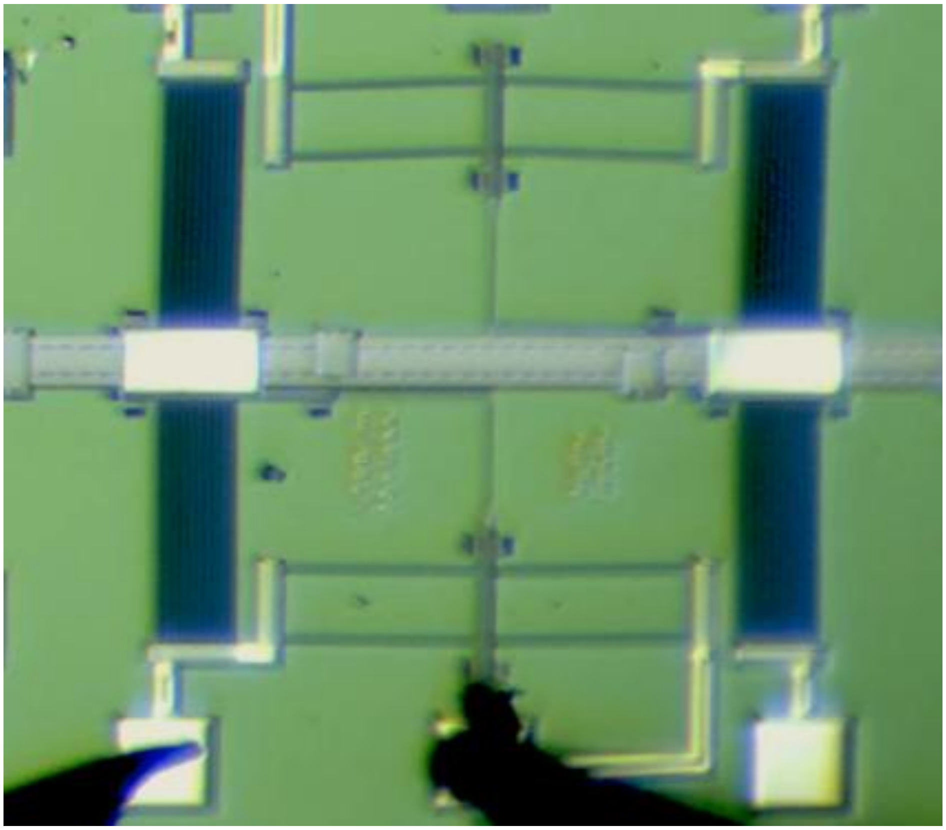


Figure 30: Electrode of MEMS Device with the Disengage Reverse Drive Actuating for Quad 555 Timer

Figure 30 shows the disengage reverse drive actuating while using the quad 555 timer system. The rest of the drives remain in the same position as the natural state. The waveforms that have been generated for this cycle is the forward drive waveform, the disengage reverse drive waveform and the disengage forward drive waveform.

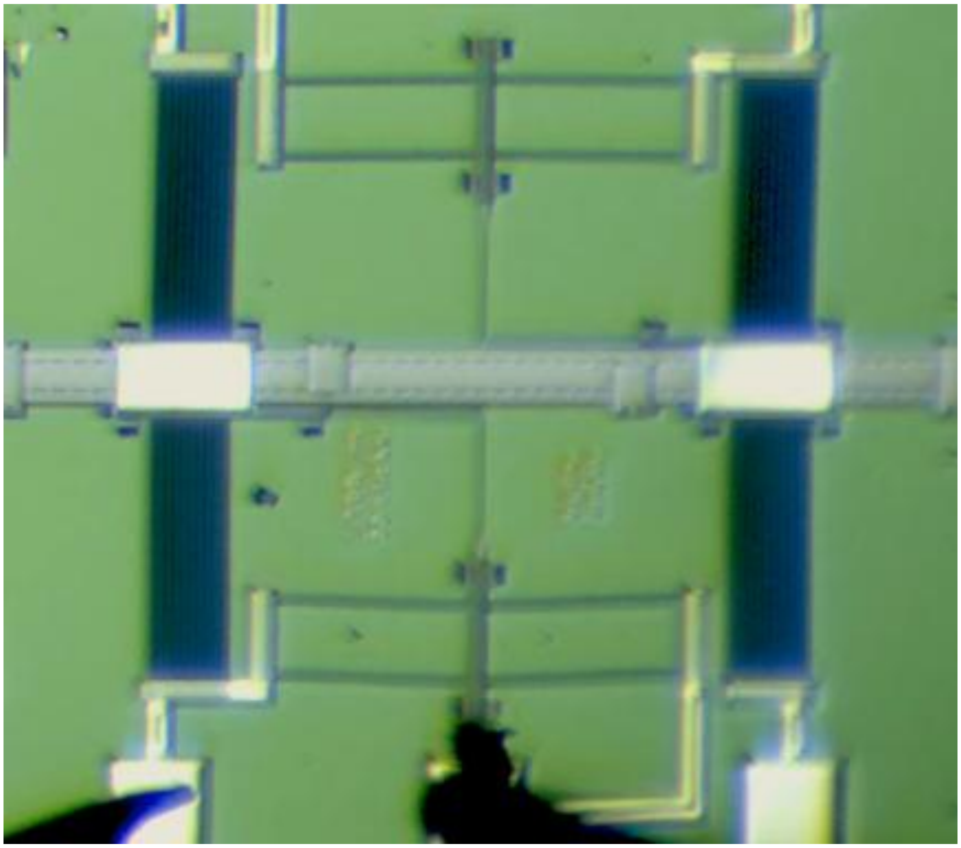


Figure 31: Electrode of MEMS Device with the Disengage Forward Drive Actuating for Quad 555 Timer

Figure 30 shows the disengage forward drive actuating while using the quad 555 timer system. The rest of the drives remain in the same position as the natural state. Both figure 30 and 31 uses the same waveforms. However, while 3 waveforms are provided, only 2 of the drives are moving, the disengage reverse and the disengage forward drive. The forward drive fails to move. The cause of this failure is the lack of enough current to power the forward drive. The disengage reverse and disengage forward drives have only 2 strips of wires. The forward drive, as well as the reverse drive, however, has 10 strips of wires. Therefore, the current required to move it is much greater than the disengage forward and disengage reverse drives. The current required to move the forward drive is

25mA. The current the quad 555 timer system provides is 19mA, thus making the system unable to ova the forward drive.

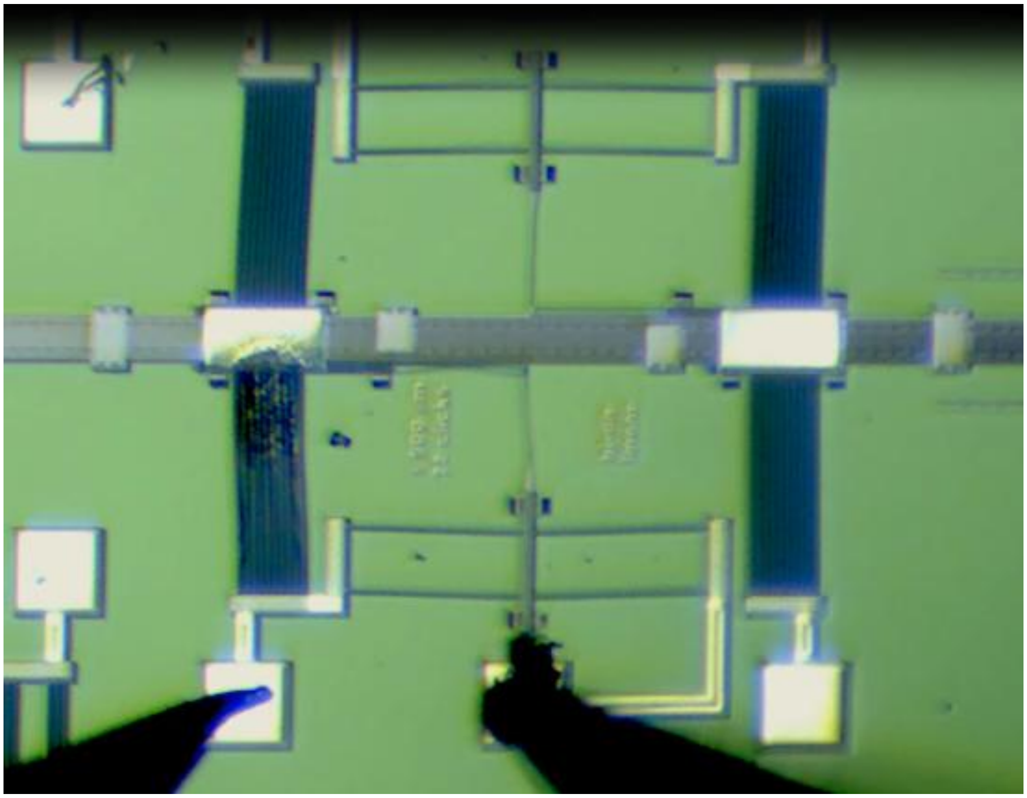


Figure 32: Electrode of MEMS Device with the Forward Drive and Disengage Forward Drive Actuating for Dual 555 Timer

Figure 32 shows the MEMS movable electrode with the forward drive and disengage forward drive moving. The rest of the drives remain in the same position as the natural state.

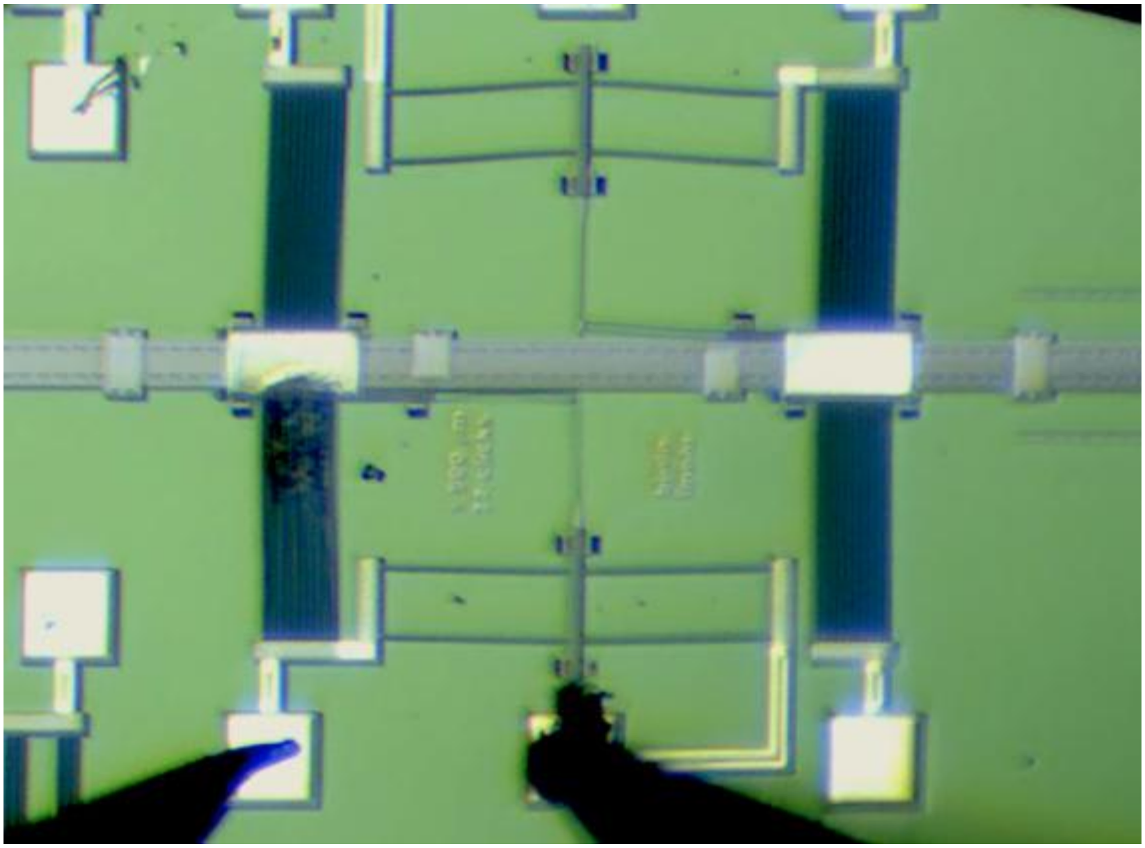


Figure 33: Electrode of MEMS Device with the Disengage Reverse Drive Actuating for Dual 555 Timer

Figure 33 shows the MEMS movable electrode with the disengage reverse drive moving. The rest of the drives remain in the same position as the natural state. The results observed by figure 32 and figure 33 are from one cycle of the dual 555 timer system. A dual 555 timer is used in place of a quad 555 timer. As observed, the forward drive is moving when the dual 555 timer system is used. The current output of the dual 555 timer system is 100mA, which is sufficient to move the forward drive.

CHAPTER 7

CONCLUSION AND FUTURE WORK

Although the quad 555 timer can produce the correct waveform at the correct voltage to actuate the electrodes, it does not have sufficient current to drive the forward and reverse drive since they have more strips and therefore, has more resistance. The maximum current output, as shown in table 3, is 23mA, however, the current required to drive the forward and reverse drives is greater than that. The alternate design using the dual 555 timer, however, can produce a maximum current of 100mA, thus, enabling it to drive the forward and reverse drives. Also, due to the exposed internal wirings, the system is influenced by noise. A container box is used to solve this problem by reducing the noise.

There are many ways to improve the SoP system. In the future, The SoP can be made into a single system-on-chip. The ASCII files from the demultiplexer and the 555 timer are needed to realize this. The files of the comparators are needed from the 555 timers and the latches, inverter, OR, NAND, NOR gates, and the buffer are needed from the demultiplexer. The schematic can be designed in Cadence and the layout can be generated from the schematic. The system-on-chip can be integrated with the microcontroller to make a complete system for actuating the MEMS device. Also, for the immediate future, a more professional packing system can be used to package the system to reduce the exposed wires, and in turn reducing the noise affecting the system.

The final outcome of this project can be used not only for neural applications, but also for more general applications that requires customized signal generations and wireless data transmission.

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APPENDIX A

DATA COLLECTED JANUARY-APRIL 2012

CODE FOR OPERATING THE MICROCONTROLLER FOR THE SYSTEM-ON-PACKAGE

```
//Defining pins on the microcontroller
int pin1 = 13;    // Trigger Waveform
int pin2 = 12;    // Trigger Waveform
int pin3 = 11;    // Trigger Waveform
int pin4 = 10;    // Trigger Waveform
int pin5 = 6;    // Select Signal A0
int pin6 = 7;    // Select Signal A1
int pin7 = 8;    // Select Signal A2
int pin8 = 9;    // Select Signal A3

void setup() {
  Serial.begin(115200);
  pinMode(pin1, OUTPUT);       // Set pin as output
  pinMode(pin2, OUTPUT);       // Set pin as output
  pinMode(pin3, OUTPUT);       // Set pin as output
  pinMode(pin4, OUTPUT);       // Set pin as output
  pinMode(pin5, OUTPUT);       // Set pin as output
  pinMode(pin6, OUTPUT);       // Set pin as output
}

void loop() {
  if (Serial.available() > 0) {
    char value = Serial.read();      // Reading the input
    if (value == 'a') {              //E1 Forward

      //Select E1    Demux Output 0              A3A2A1A0 = 0000 The 555 Timer will
reverse the signal, so we want A3A2A1A0 = 0000,
      //                                                    we provide A3A2A1A0 = 1111;
      digitalWrite(pin5, HIGH);
      digitalWrite(pin6, HIGH);
      digitalWrite(pin7, HIGH);
      digitalWrite(pin8, HIGH);

      // Forward Waveform
```

```
    digitalWrite(pin1, LOW);
    digitalWrite(pin2, HIGH);
    digitalWrite(pin3, LOW);
    digitalWrite(pin4, LOW);
    delay(1);
    digitalWrite(pin1, HIGH);
    delay(1);
    digitalWrite(pin2, LOW);
    delay(1);
    digitalWrite(pin4, HIGH);
    delay(1);
    digitalWrite(pin1, LOW);
    delay(1);
    digitalWrite(pin4, LOW);
  }
  else if (value == 'b') {            //E1 Reverse
    //Select E1     Demux Output 0          A3A2A1A0 = 0000  The 555 Timer will
reverse the signal, so we want A3A2A1A0 = 0000,
    //                                            we provide A3A2A1A0 = 1111;
    digitalWrite(pin5, HIGH);
    digitalWrite(pin6, HIGH);
    digitalWrite(pin7, HIGH);
    digitalWrite(pin8, HIGH);

    //Reverse Waveform
    digitalWrite(pin1, LOW);
    digitalWrite(pin2, HIGH);
    digitalWrite(pin3, LOW);
    digitalWrite(pin4, LOW);
    delay(1);
    digitalWrite(pin3, HIGH);
    delay(1);
    digitalWrite(pin2, LOW);
    delay(1);
    digitalWrite(pin4, HIGH);
    delay(1);
    digitalWrite(pin3, LOW);
```

```
    delay(1);
    digitalWrite(pin4, LOW);
  }
   else if (value == 'c') {           //E2 Forward
    //Select E2      Demux Output 2        A3A2A1A0 = 0001  The 555 Timer will reverse
the signal, so we want A3A2A1A0 = 0001,
    //                                                       we provide A3A2A1A0 = 1110;
    digitalWrite(pin5, LOW);
    digitalWrite(pin6, HIGH);
    digitalWrite(pin7, HIGH);
    digitalWrite(pin8, HIGH);

    // Forward Waveform
    digitalWrite(pin1, LOW);
    digitalWrite(pin2, HIGH);
    digitalWrite(pin3, LOW);
    digitalWrite(pin4, LOW);
    delay(1);
    digitalWrite(pin1, HIGH);
    delay(1);
    digitalWrite(pin2, LOW);
    delay(1);
    digitalWrite(pin4, HIGH);
    delay(1);
    digitalWrite(pin1, LOW);
    delay(1);
    digitalWrite(pin4, LOW);
  }
  else if (value == 'd') {            //E2 Reverse
    //Select E2      Demux Output 2        A3A2A1A0 = 0001  The 555 Timer will reverse
the signal, so we want A3A2A1A0 = 0001,
    //                                                       we provide A3A2A1A0 = 1110;
    digitalWrite(pin5, LOW);
    digitalWrite(pin6, HIGH);
    digitalWrite(pin7, HIGH);
    digitalWrite(pin8, HIGH);
```

```
    //Reverse Waveform
    digitalWrite(pin1, LOW);
    digitalWrite(pin2, HIGH);
    digitalWrite(pin3, LOW);
    digitalWrite(pin4, LOW);
    delay(1);
    digitalWrite(pin3, HIGH);
    delay(1);
    digitalWrite(pin2, LOW);
    delay(1);
    digitalWrite(pin4, HIGH);
    delay(1);
    digitalWrite(pin3, LOW);
    delay(1);
    digitalWrite(pin4, LOW);
  }
  else if (value == 'e') {          //E3 Forward
    //Select E3      Demux Output 3        A3A2A1A0 = 0010  The 555 Timer will reverse
the signal, so we want A3A2A1A0 = 0010,
    //                                                  we provide A3A2A1A0 = 1101;
    digitalWrite(pin5, HIGH);
    digitalWrite(pin6, LOW);
    digitalWrite(pin7, HIGH);
    digitalWrite(pin8, HIGH);

    // Forward Waveform
    digitalWrite(pin1, LOW);
    digitalWrite(pin2, HIGH);
    digitalWrite(pin3, LOW);
    digitalWrite(pin4, LOW);
    delay(1);
    digitalWrite(pin1, HIGH);
    delay(1);
    digitalWrite(pin2, LOW);
    delay(1);
    digitalWrite(pin4, HIGH);
    delay(1);
```

```
    digitalWrite(pin1, LOW);
    delay(1);
    digitalWrite(pin4, LOW);
  }
  else if (value == 'f') {            //E3 Reverse
    //Select E3     Demux Output 3       A3A2A1A0 = 0010  The 555 Timer will reverse
the signal, so we want A3A2A1A0 = 0010,
    //                                                 we provide A3A2A1A0 = 1101;
    digitalWrite(pin5, HIGH);
    digitalWrite(pin6, LOW);
    digitalWrite(pin7, HIGH);
    digitalWrite(pin8, HIGH);

    //Reverse Waveform
    digitalWrite(pin1, LOW);
    digitalWrite(pin2, HIGH);
    digitalWrite(pin3, LOW);
    digitalWrite(pin4, LOW);
    delay(1);
    digitalWrite(pin3, HIGH);
    delay(1);
    digitalWrite(pin2, LOW);
    delay(1);
    digitalWrite(pin4, HIGH);
    delay(1);
    digitalWrite(pin3, LOW);
    delay(1);
    digitalWrite(pin4, LOW);
  }
  else if (value == 'z') {
    digitalWrite(pin3, HIGH);
    delayMicroseconds(1000);
    digitalWrite(pin1, LOW);
  }
  else {
//      digitalWrite(pin3, LOW);
  }
```

```
    Serial.println(value);
  }
//  delay(1000);
}
```