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Prototyping a Capacitive Sensing Device for Gesture Recognition

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Prototyping a Capacitive Sensing Device for Gesture Recognition

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Abstract

Capacitive sensing is a technology that can detect proximity and touch. It can also be utilized to measure position and acceleration of gesture motions. This technology has many applications, such as replacing mechanical buttons in a gaming device interface, detecting respiration rate without direct contact with the skin, and providing gesture sensing capability for rehabilitation devices. In this thesis, an approach to prototype a capacitive gesture sensing device using the Eagle PCB design software is demonstrated. In addition, this paper tested and evaluated the resulting prototype device, validating the effectiveness of the approach.

Acknowledgments

I would like to express my sincere gratitude to Dr. Pat Parkerson and Dr. Alexander Nelson for their mentorship in this research project. Their encouragement and expertise helped me grow as a researcher and writer. I would also like to thank Dr. David Andrews for serving in my honors thesis defense committee and providing feedback and recommendations regarding my thesis.

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Chapter 1: Introduction

1.1 Problem

According to the American Heart Association, approximately a million individuals in the U.S. are hospitalized annually due to brain injuries, spinal cord injuries, and new or recurring strokes [1, 2, 3]. Trauma due to stroke or physical injury typically requires a long-term rehabilitation process to recover. The long-term conventional hospital-based rehabilitation strategy is costly at around $75,000 per year in average [5]. Home-based rehabilitation strategy is less expensive compared to conventional hospital-based rehabilitation [4]. While home-based rehabilitation does not demonstrate superior improvements in recovery rate when compared to conventional hospital-based rehabilitation, it shows significant improvements in the level of psychosocial well-being, caregiver outcomes, and general health [5]. Therefore, the development of an affordable home-based rehabilitation device is critical.

To solve the issue mentioned above, Liu et al. designed an affordable gesture sensing device for upper-extremity motor rehabilitation using the capacitive sensing array technology [6]. This gesture sensing device uses a MSP430 development board to process the capacitive gesture data as shown in figure 1. However, the MSP430 development board is designed with many redundant functions that are not needed for the purpose of capacitive sensing, which increased the size and price of the sensing prototype.

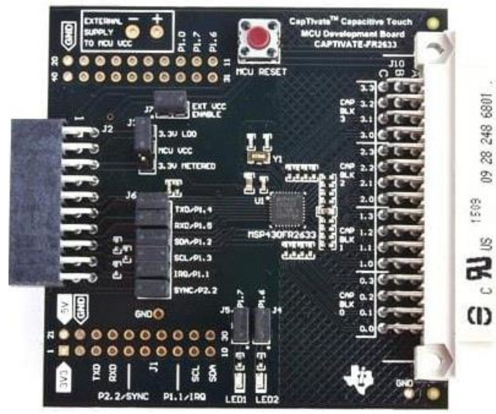

Figure 1: MSP430 development board

1.2 Thesis statement

The main purpose of this paper is to design a prototype capacitive sensing device based on a MSP430 MCU chip that is smaller and cheaper compared to the original MSP430 development board.

1.3 Approach

The proposed solution in this paper is to redesign the MSP430 development board using the Autodesk Eagle PCB design software. The redesigned board will only keep the essential functions for capacitive sensing which lowers the cost and saves the board space.

Chapter 2: Background

2.1 MSP430FR2633 MCU

The system-on-chip MSP430FR2633 is a popular 16-bit, ultra-low-power capacitive sensing & measurement MCU (microcontroller unit). It offers 16 capacitive sensing channels for up to 16 self-capacitance or 64 mutual-capacitance sensors. This

MCU also offers several optimized power modes — ACTIVE, LPM0, LPM3, LPM3.5, LPM4, LPM4.5 — for different power applications [9].

2.2 Capacitance

To understand how capacitive sensing works, we must understand the fundamental properties and principles of capacitance. The capacitance is the ability of an electric conductor or set of conductors to store electrical charges. A common capacitor used in the electrical circuit consists of two parallel conductive plates. The capacitance of the capacitor C is measured by the amount of separated electric charges Q stored in the conductors per electrical potential V between the conductors as shown in Equation (1) [7].

$$C = \frac{Q}{V} \quad (1)$$

Another way of measuring the capacitance C is to use the area of the conductors A and the distance d between them as shown in Equation (2). In Equation (2), symbol k is the relative permittivity of the dielectric material between the plate conductor, and symbol ε_0 is the permittivity of free space.

$$C = \frac{\varepsilon_0 k A}{d} \quad (2)$$

Using Equation (2), we can derive the graphs in figure 2 and in figure 3. Figure 2 shows the relationship between the separation distance of the conductors and the capacitance. Figure 3 shows the relationship between the area of the conductors and the capacitance.

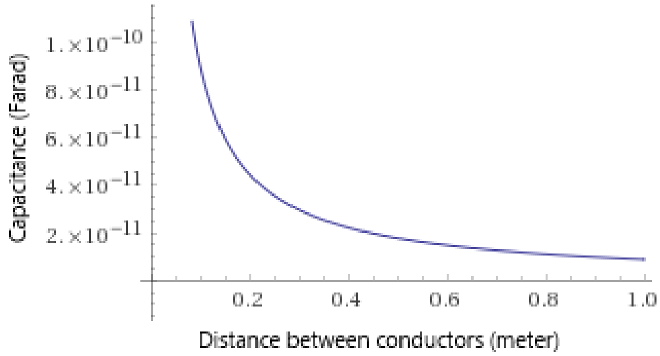

Figure 2: Capacitance with respect to the distance between conductors

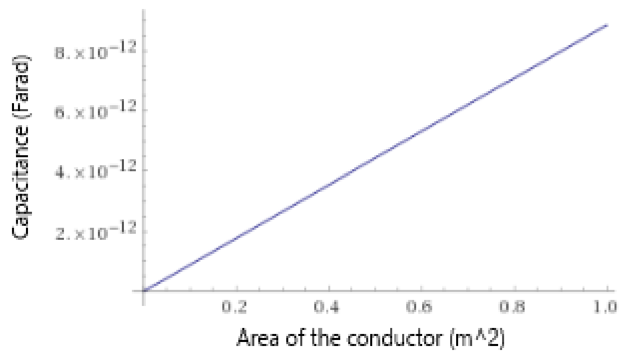

Figure 3: Capacitance with respect to the area of the conductor

2.3 Capacitive sensing

The capacitive sensors can operate in two modes — self-capacitance detection or mutual-capacitance detection.

2.3.1 Self-capacitance detection

In self-capacitance detection mode, a capacitive channel forms a capacitive sensor. This capacitive sensor can be modeled as a capacitor with the upper plate connected to the sensing pad and the bottom plate connected to the Earth. As the user's finger gets in the vicinity of the capacitive sensor, a portion of the positive charges polarizes the tip of the finger, forming another capacitor with reference to the Earth as shown in figure 4a [10].

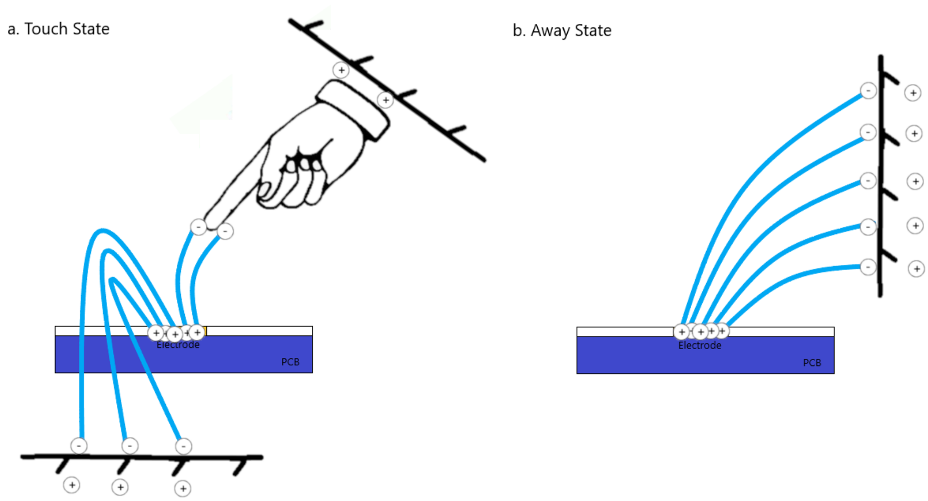

Figure 4: Self-capacitance detection (a) Touch state (b) Away state

The effective capacitance of the capacitive sensor during the touch event can be modeled with the parallel capacitors formula shown in Equation (3).

$$C_{Effective} = C_{Electrode} + C_{Finger} \tag{3}$$

2.3.2 Mutual-capacitance detection

In mutual-capacitance detection mode, a capacitive channel no longer forms a capacitor with reference to the Earth. Instead, it forms a capacitor with another capacitive channel. The positively charged upper plate is the Tx channel and the negatively charged lower plate is the Rx channel. In contrary to the self-capacitance detection mode, the effective capacitance of the capacitive sensor does not increase with the "touch" event, instead it decreases. This phenomenon is due to a portion of the positive charges at the Tx channel polarizing the user's fingertip, reducing effective charges between the Tx channel and Rx channel [10]. With Equation (1), it is demonstrable that the reduction of capacitance is the result of a touch event.

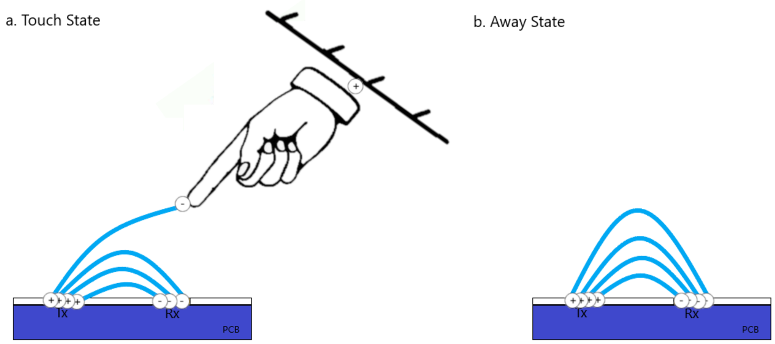

Figure 5: Mutual-capacitance detection (a) Touch state (b) Away state

The mutual-capacitance mode is best employed as a capacitive array. The array maximizes the number of capacitive sensors using the least number of capacitive channels. For example, by evenly dividing 16 capacitive channels into 8 Tx and 8 Rx channels and overlaps each channel into an array, 64 capacitive sensors can be obtained as shown in figure 6.

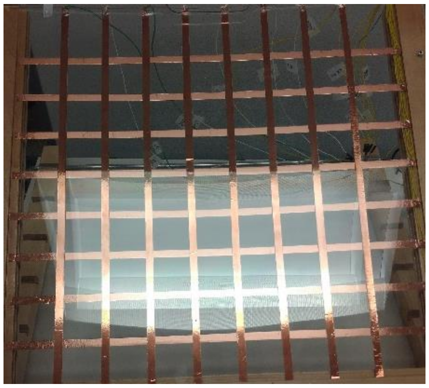

Figure 6: Capacitive sensor array with 64 sensors

2.3.3 Charge Transfer Method

To detect the change in capacitance at the capacitive sensor due to proximity and touch events, the MSP430 MCU uses a technique called charge transfer method [10]. With this method, a larger internal reference capacitor is used to discharge the capacitive sensor. Every time the capacitive sensor discharges, the capacitance counter of that capacitive sensor is incremented by one. This process is stopped when the voltage across the internal reference capacitor reaches the trip voltage [10]. The final count value is then reported. This count value can be compared with the count value from the last cycle to determine the away and touch event at the capacitive sensor.

Chapter 3: Design and Implementation

3.1 Schematic design

The first step in the PCB design process is to determine the functional requirements of the PCB board and design a schematic for it.

3.1.1 MSP430FR2633 MCU and ESD (Electrostatic discharge) protection

In this paper, a MSP430FR2633 IDA packaging MCU with 16 capacitive channels is used as our capacitive processor. To gain access to each of these channels, 16 header pins are connected to these channels. In additions to these header pins, we place a 470 ohms series resistor on each channel to prevent damage to the circuit by ESD [9].

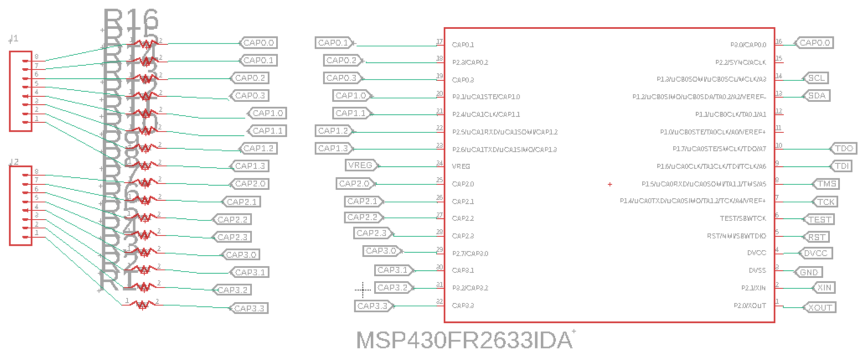

Figure 7: MSP430FR2633 and electrostatic discharge protection circuit schematic

3.1.2 Clock module

Although the MSP430FR2633 MCU has an on-chip 32kHz RC oscillator [9], an external 32kHz Pierce crystal oscillator can help facilitate more accurate, stable waves and is less power consuming [12]. In addition to the crystal oscillator, two 22pf capacitors are required as a load for the crystal oscillator [11].

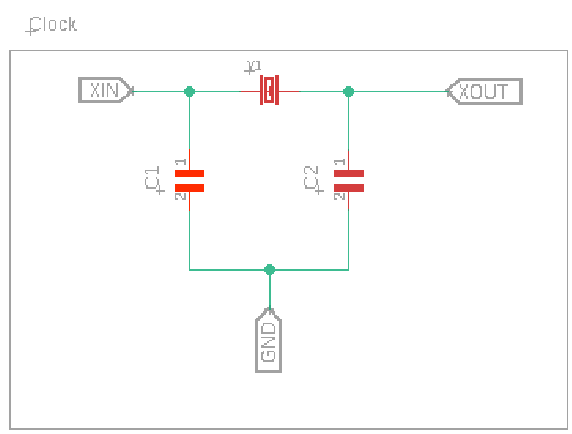

Figure 8: A 32kHz external Pierce oscillator circuit

3.1.3 Data communication

To access capacitive sensor readings, two header pins are connected to I2C pins at the MSP430FR2633 chip.

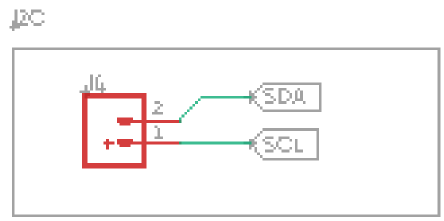

Figure 9: I2C data and clock pins connecting to header pins

3.1.4 Programming

To program the MSP430FR2633 chip, a tag-connect connector is connected to JTAG pins at the chip. A JTAG power jumper is added to give the user an option to power the chip by the programmer or by onboard power.

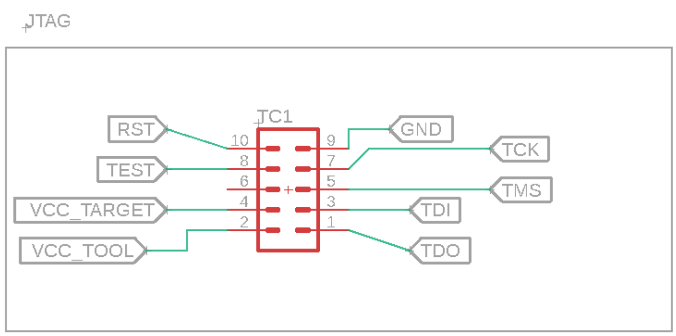

Figure 10: MSP430 JTAG pins connecting to a tag-connect device

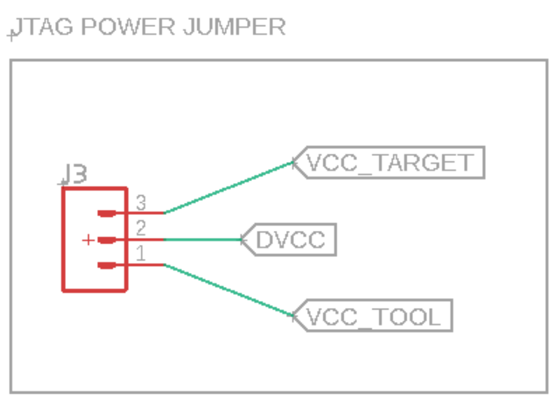

Figure 11: MSP430 JTAG Power jumper

3.1.5 Reset

To reset the chip without disconnect the power, a pull-up switch circuit is designed. Resistor R20 is a pull-up resistor that sets a high state at the active low reset pin when the switch is open. Capacitor C7 is a pull-down capacitor for switch debouncing when the switch is pressed.

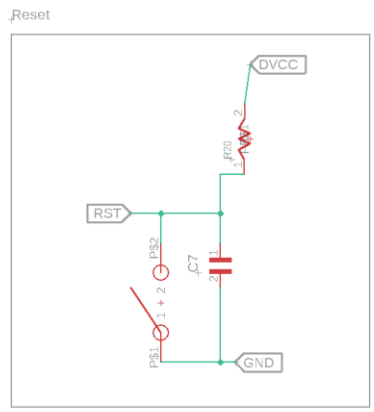

Figure 12: A switch reset circuit

3.1.6 Power and LED indicator

A LED and a ballast resistor are used for “On/Off” indicator as shown in figure 13. In figure 14, power decoupling capacitors are used for voltage smoothing.

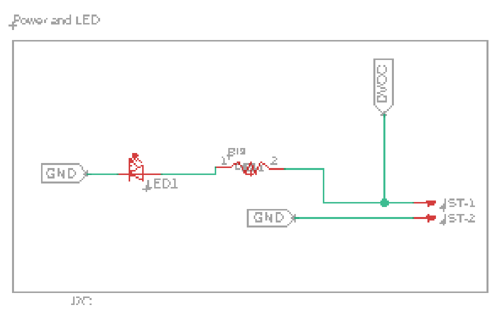

Figure 13: Power indicator and Power connector

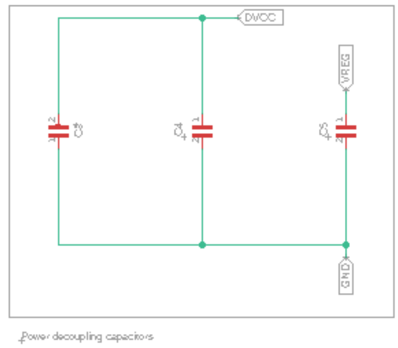

Figure 14: Power decoupling capacitors

3.2 Eagle — Library and Device

The second step of the PCB design process is to transfer the designed schematic into the Eagle design software. Before drawing the schematic in Eagle, the footprint and symbol of each device required in the schematic must be drawn first.

3.2.1 Library and Device

The library is a collection of devices. A device is an electronic component consisting of a footprint and a symbol [8]. For example, the MSP430FR2633 chip is a device.

3.2.2 Footprint

The footprint provides information about the physical layout of the device, such as the location of the pins. The footprint of a device represents the device at the Eagle placement and route panel.

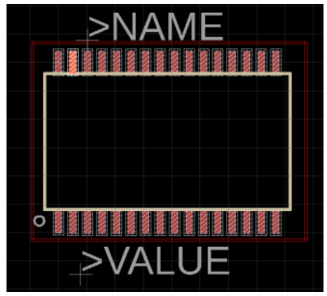

Figure 15: MSP430FR2633IDA footprint

3.2.3 Symbol

The symbol is an abstract, graphical representation of the device. The symbol of a device represents the device at the Eagle schematic drawing panel.

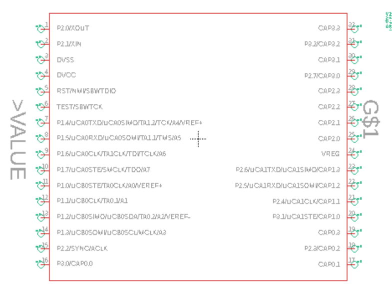

Figure 16: MSP430FR2633IDA symbol

3.3 Eagle — Schematic

The third step of the PCB design process is to connect devices together according to the designed schematic.

3.3.1 Nets and Net tagging

In the Eagle schematic drawing panel, the net tool can be used to electrically connect the devices together. However, when drawing a complicated circuit, the net tool alone is not very great for creating an elegant schematic. This is when the net tagging technique comes in to help. The net tagging technique allows the schematic designer to tag nets with the name tool. Nets that were assigned to the same tag name are electrically connected.

3.3.2 ERC (Electrical rule check)

Once all devices are connected electrically according to the designed schematic, the ERC tool can be used to check for fatal error or warnings.

3.4 Eagle — Placement and Route

The fourth step of the PCB design process is the placement of devices and electrical net/traces.

3.4.1 Routing — trace and via

In Eagle route and placement panel, after dragging devices to the desired location on the board, the route tool is used to manually route the copper traces. The copper traces and the devices can be placed onto the top (layer 1) or the bottom (layer 16) of the PCB board. The via can be used to electrically connect traces of both layers. Do not draw any right-angle traces, because it will introduce some signal delay and excess capacitance at the bend [13].

3.4.2 Hatched ground

The capacitive channels are very sensitive to the local parasitic capacitances [9]. By placing a hatched ground shield around the capacitive channels, we can minimize noises due to local parasitic capacitances and maximize the effect of external changing capacitance (touch event) [9].

3.4.3 Silkscreen

The silkscreen is labels imprinted onto the PCB to help the manufacturer and engineers identify the components and devices. The silkscreen can be placed onto the top (layer 25) or bottom (layer 26) of the PCB board using the text tool. Figure 17 shows a version control silkscreen.

Figure 17: A version control silkscreen

3.4.4 Ratsnest

The ratsnest tool can be used to connect all air-wires (unconnected wires) with the shortest possible path. In a combination with the polygon tool, the ratsnest tool can also be used to create ground plates.

3.4.5 Crystal oscillator placement

The Crystal oscillator module must be placed as close to the MSP430 microcontroller as possible to reduce parasitic capacitance and inductance. High parasitic capacitance and inductance could affect the load capacitance of the crystal oscillator, causing it to generate incorrect oscillation frequency [11].

3.4.6 Captivate VREG (LDO voltage regulator) decoupling capacitor placement

The 1-μF decoupling capacitor (C5) must be placed as close to the microcontroller as possible [9].

3.4.7 DRC (Design rule check)

After the placement and routing have completed, the DRC tool can be used to check for errors, such as air-wires and clearance.

3.5 Manufacture and Soldering

The final step of the PCB design process is manufacturing the board and soldering the surface mounted components onto the board. OSH Park was used for fabricating the prototype PCB boards. Upon receiving the board from the manufacturer, the boards are populated with components and soldered.

3.5.1 Pre-tin pads

When soldering small SMD components, pre-tinning the solder pads with a light amount of solder can be helpful.

3.5.2 Solder paste

When soldering the SMD components with small, tightly spaced pins, low-temperature solder paste can be helpful.

3.6 Programming

In order to do capacitive sensing, the MSP430 chip must be programmed.

3.6.1 Captivate design center

The manufacturer of Captivate MSP430 chip, Texas Instruments, has provided us the captivate design center software to configure the MSP430 chip. The user can configure settings, such as mode of detection, communication interface, and pin assignments. Once the configuration is properly tuned, this tool can generate a code composer studio project for the next step of the programming process.

Figure 18: A capacitive sensor configured in mutual-capacitance detection mode

3.6.2 Code composer studio and MSP-FET programmer

The last step of the MSP430 programming requires an MSP-FET programmer and the code composer studio software. To finish programming the chip, start by loading up the project file in the code composer studio software, then connect the computer and the MSP430 JTAG pins via the MSP-FET programmer. By clicking the build and run button in the code composer studio graphical interface, the chip is programmed.

Chapter 4: Test and Evaluation

4.1 Board specification

To begin, figure 22 illustrates a photo of the MSP430 development board alongside a redesigned MSP430 board. Immediately, you can see the size difference. The size of MSP430 development board is 7.5 cm by 6 cm. In comparison, the redesigned MSP430 board only measured at 4 cm by 4 cm. Furthermore, the price of the MSP430 development board is 20 dollars, while the redesigned MSP430 board only cost around 9 dollars to build.

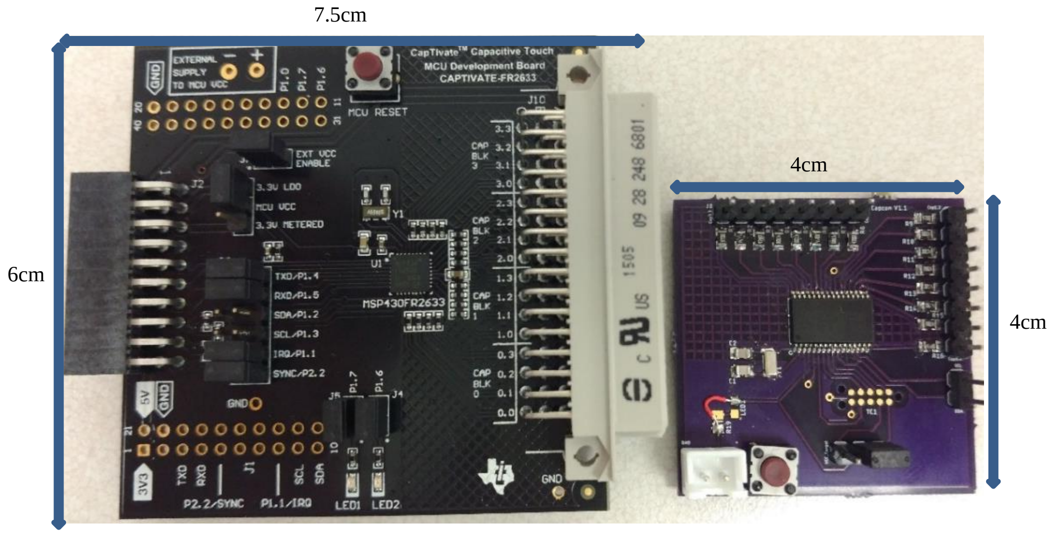

Figure 19: MSP430 development board and redesigned MSP430 board

4.2 Self-capacitance and Mutual-capacitance mode test

To verify the design of the PCB board, A channel is programmed to run in the self-capacitance mode and two other channels in mutual-capacitance mode. Figure 20 and figure 21 illustrates the change in capacitance count with respect to the size of the "touching" object and the distance of the "touching" object for both detection modes. Note that as the distance decreases, the self-capacitance sensor count is growing in the negative direction, and the mutual capacitance sensor count is growing in the positive direction. This is due to the same phenomenon we discussed in the background chapter.

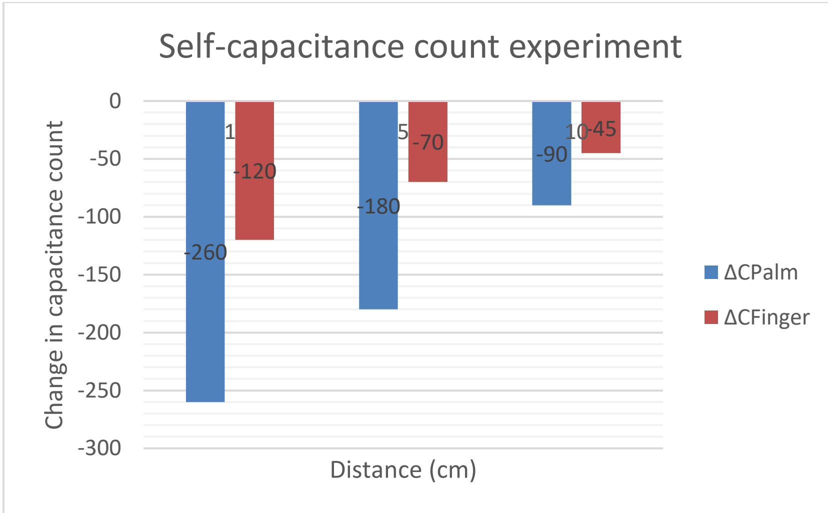

Figure 20: Self-capacitance sensor counter experiment

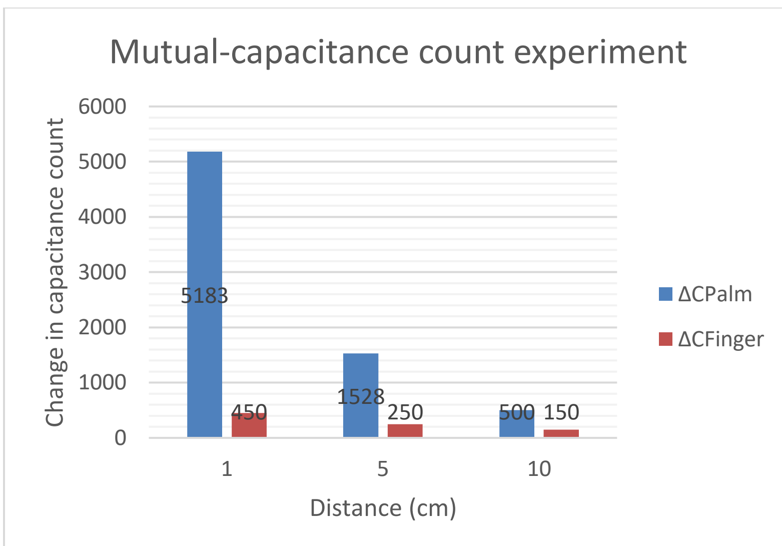

Figure 21: Mutual-capacitance sensor counter experiment

4.3 Power consumption

Using an oscilloscope and an ultra-sensitive current probe, the power consumption of the PCB board is measured. In this power evaluation experiment, the MSP430 chip is configured at 50 Hz scanning rate and varying power modes. Each power mode is assigned a minute of sampling time. During the experiment, it is observed that in power mode LPM3 and LPM4, the performance of the chip is sacrificed by reducing clock speed and disabling peripherals [10]. Due to slower clock speed, LPM3 and LPM4 are less power consuming than LPM0 as shown in figure 22, 23, and 24.

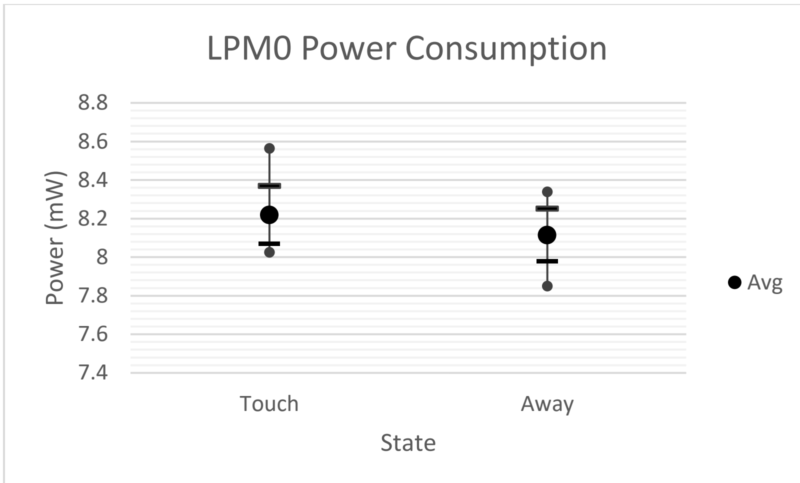

Figure 22: LPM0 Power Consumption

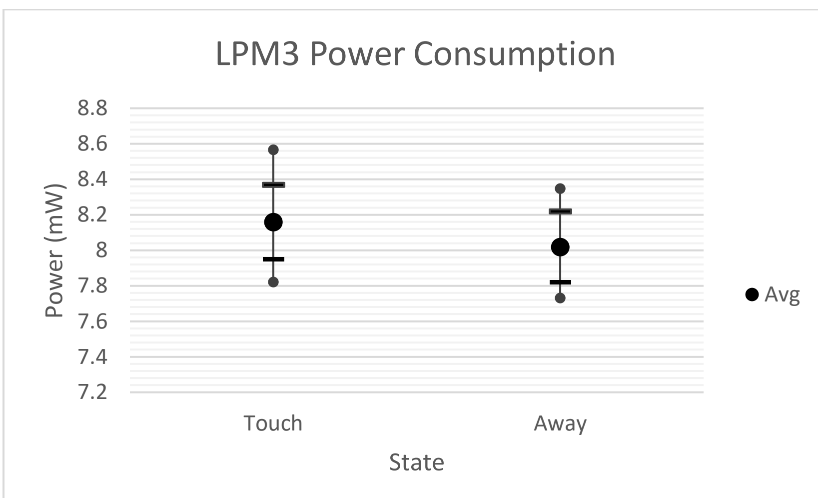

Figure 23: LPM3 Power Consumption

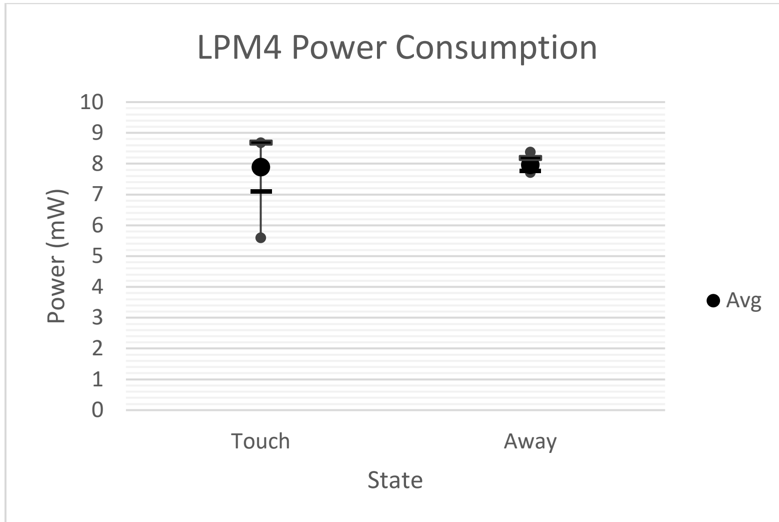

Figure 24: LPM3 Power Consumption

Chapter 5: Conclusion and Future work

5.1 Conclusion

This paper proposes an approach to prototype a capacitive sensing device for gesture recognition using the Eagle PCB design software. This paper then implements this approach and evaluates the resulting prototype device. This prototype device is about 11 dollars cheaper and 3 times smaller than the original one. More importantly, this prototype device retained all capacitive sensing functionalities from the original device. Consequently, this device design enabled a way to produce more affordable gesture sensing rehabilitation devices for needed patients. In addition, this device can be further applied to a gaming device interface, respiration rate acquisition, and home automation.

5.2 Future work

Although this prototype device is cheaper and smaller than the original one, there is still room for improvements. In this design, by replacing header pins with a flat flexible connector, the size of the board will decrease considerably. Also, replacing the resistors and the capacitors with their counterparts in a smaller footprint will also help reduce the board size.

References

[1] E. J. Benjamin, S. S. Virani, and C. W. Callaway. 2018. Heart Disease and Stroke Statistics-2018 Update: A Report From the American Heat Association. Circulation 17, 12 (2018), 493.

[2] National Spinal Cord Injury Statistical Center. 2018. Facts and Figures at a Glance. Univ. Alabama Birmingham, Birmingham, AL, USA.

[3] C. A. Taylor, J. M. Bell, M. J. Breiding, and L. Xu. 2017. Traumatic Brian Injury-Related Emergency Department Visits, Hospitalization, and Deaths. MMWR. Surveillance Summaries 66, 9 (2017), 1–16.

[4] M. Britton and A. Andersson, "HOME REHABILITATION AFTER STROKE: Reviewing the Scientific Evidence on Effects and Costs," *International Journal of Technology Assessment in Health Care*, vol. 16, no. 03, pp. 842–848, 2000.

[5] Allen, Laura J., "A Cost-Effectiveness Study of Home-Based Stroke Rehabilitation" (2015). Electronic Thesis and Dissertation Repository. 2900. https://ir.lib.uwo.ca/etd/2900

[6] H. Liu, J. P. Parkerson and A. Nelson, "Connected Capacitive Sensor Array for Upper-Extremity Motor Rehabilitation," *2018 IEEE/ACM International Conference on Connected Health: Applications, Systems and Engineering Technologies (CHASE)*, Washington, DC, USA, 2018, pp. 17-18.

[7] Britannica Academic, s.v. "Capacitance," accessed April 17, 2019, https://0-academic-eb-com.library.uark.edu/levels/collegiate/article/capacitance/20105.

[8] WALLACE, S. (2018). Jumpstarting Your Own PCB: Learn How to Design and Make Customized Circuit Boards. 1st ed. San Francisco, CA: O'REILLY MEDIA.

[9] *MSP430FR263x, MSP430FR253x Capacitive Touch Sensing Mixed-Signal Microcontrollers*, Texas Instruments Inc., Dallas, TX, 2018.

[10] *MSP430FR4xx and MSP430FR2xx Family User's Guide*, Texas Instruments Inc., Dallas, TX, 2018.

[11] *MSP430 32-kHz Crystal Oscillators*, Texas Instruments Inc., Dallas, TX, 2017.

[12] *MSP430 Initialization & Clocking*, Texas Instruments Inc., Dallas, TX, 2018.

[13] Johnson, H. (2000). Who's afraid of the big, bad bend? Edn, 45(10), 36. Retrieved from http://0-search.proquest.com.library.uark.edu/docview/222424741?accountid=8361

Appendix

Table 1: Self-capacitance sensor count experiment

Self-capacitance sensor count experiment		
Distance (cm)	ΔC_{Palm}	ΔC_{Finger}
10	-90	-45
5	-180	-70
1	-260	-120

Table 2: Mutual-capacitance sensor count experiment

Mutual-capacitance experiment		
Distance (cm)	ΔC_{Palm}	ΔC_{Finger}
10	500	150
5	1528	250
1	5183	450

Table 3: LPM0 power measurement

LPM0									
State	V_{avg}	A_{avg}(mA)	P_{avg}(mW)	V_{max}	A_{max}	P_{max}	V_{min}	A_{min}	P_{min}
Touch	3.26	2.51	8.21	3.26	2.62	8.56	3.26	2.45	8.02
Away	3.26	2.48	8.11	3.26	2.55	8.33	3.26	2.40	7.85

Table 4: LPM3 power measurement

LPM3									
State	V_{avg}	A_{avg}(mA)	P_{avg}(mW)	V_{max}	A_{max}	P_{max}	V_{min}	A_{min}	P_{min}
Touch	3.27	2.48	8.15	3.27	2.61	8.56	3.27	2.38	7.82
Away	3.27	2.44	8.01	3.27	2.54	8.34	3.27	2.36	7.73

Table 5: LPM4 power measurement

LPM4									
State	V_{avg}	A_{avg}(mA)	P_{avg}(mW)	V_{max}	A_{max}	P_{max}	V_{min}	A_{min}	P_{min}
Touch	3.27	2.4	7.88	3.28	2.63	8.64	3.27	1.7	5.59
Away	3.27	2.42	7.96	3.28	2.55	8.37	3.27	2.35	7.71

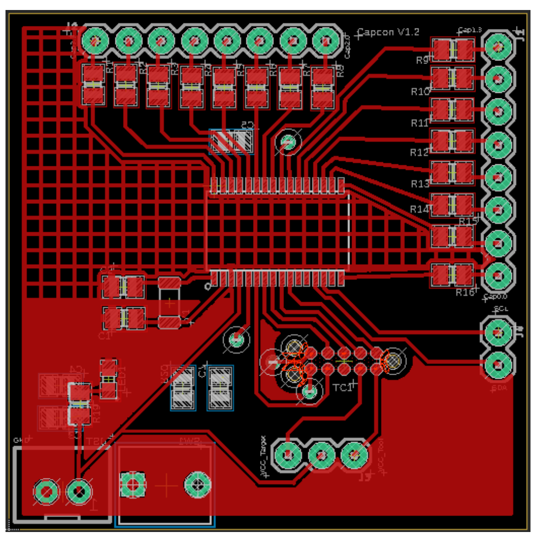

Figure 25: Top layer of the final PCB

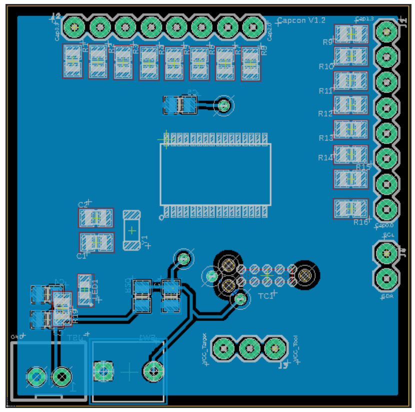

Figure 26: Bottom layer of the final PCB

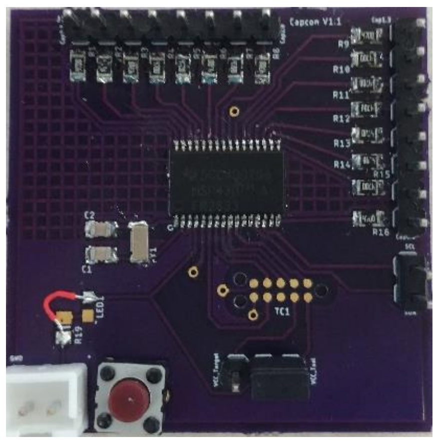

Figure 27: Top layer of the manufactured PCB board

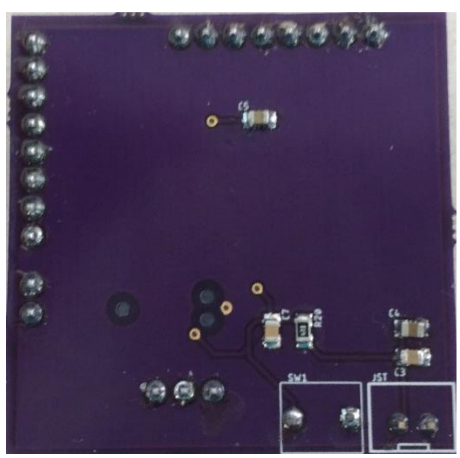

Figure 28: Bottom layer of the manufactured PCB board

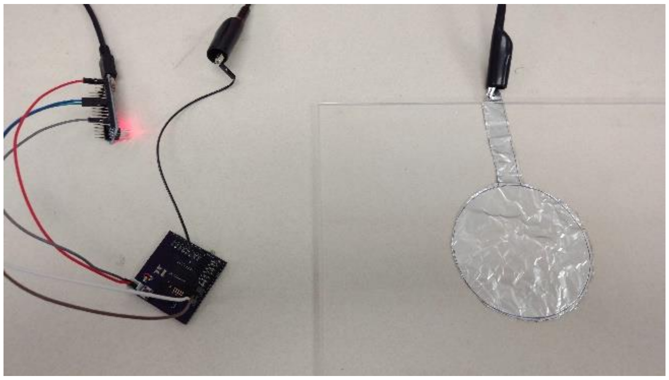

Figure 29: Single self-capacitance capacitive sensor

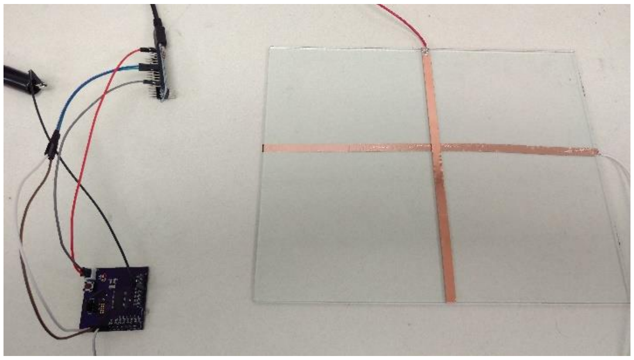

Figure 30: Single mutual-capacitance capacitive sensor