ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

ECE 445 Final Report: Electronic Martial Arts Paddles

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1 Introduction

Taekwondo (TKD) is a Korean martial art that involves various kicking techniques and forms. TKD is a popular sport in many parts of the world, where the big stage takes place at the Olympic. Athletes are put against each other to fight with electronic fighting gear with built-in sensors lent by the venue. These sensors are how points are determined when struck with some force above a certain threshold. These fighting gears are, however, prohibitively expensive at times, going up to $3000. For some small teams, it is nearly impossible to provide their athletes with these expensive but crucial gears. Consequently, a typical training session is carried out by using training tools called the "paddles." These paddles are akin to boxing mitts in boxing in which athletes train by using these paddles as targets for their kicks and punches. Coaches and athletes go by the "feel" of how well the paddles were struck, making it a poor indicator of skill and accuracy. We tackle this problem by prototyping our design of integrating sensors into the paddles themselves in conjunction with a training regimen program to help the athletes to better assess their performance, particularly in the consistent in measuring the force so it is clear to the athletes that the threshold force has been overcome like a true competitive setting.

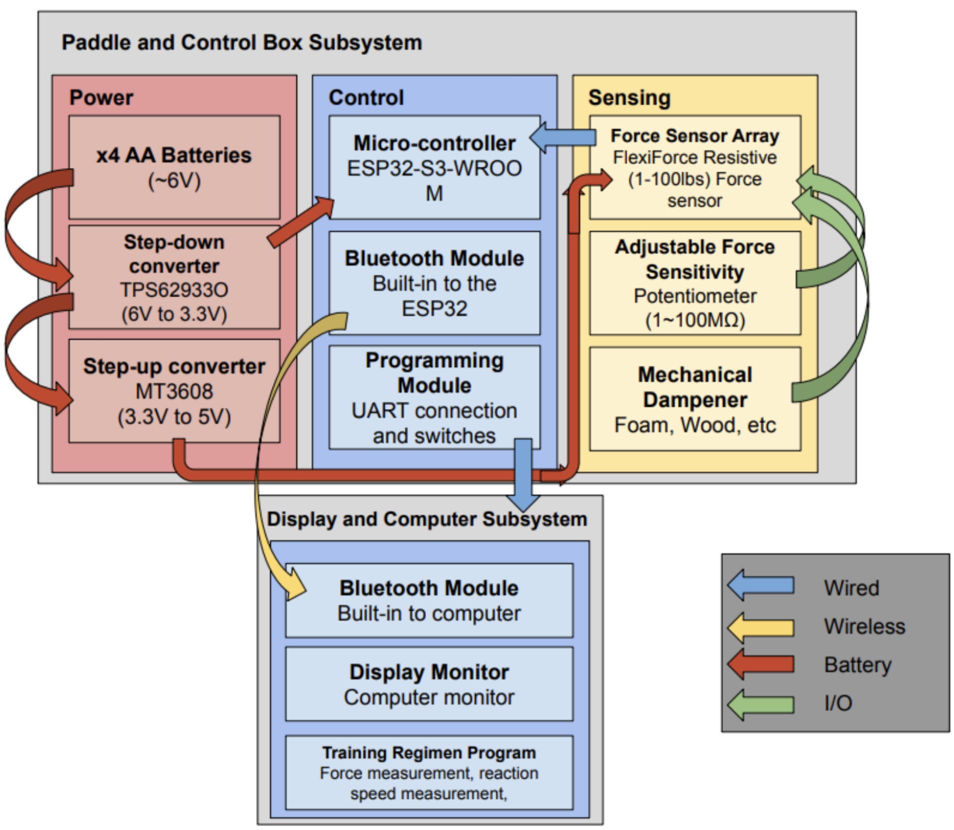

Figure 1: Block diagram of the design, with Paddle/Control Box Subsystem and Display/Computer Subsystem

The main goal of our design is to read the force measurements consistently and report back to the athletes the force measurements and the accuracy of the strike through our program. As laid out in Figure 2, the athlete will strike the force sensor integrated paddle, which is connected via wires to the printed circuit board (PCB). The PCB is held within an enclosing which is clipped onto the belt of the paddle holders/other athletes. The PCB then communicates with the computer with the training program via bluetooth.

Our Figure 2 visual aid is complemented by our block diagram in Figure 1. The paddle is powered by four AA batteries, which handles the power for the entire design, from the microcontroller to the individual force sensors. Two force sensors are integrated in between the opening of the paddles, padded between foam and sponge to provide cushioning and stability in the paddles. The force sensors read force exerted onto themselves and convert those values to voltage, which is sent to our microcontroller, ESP32. The ESP32, with its built-in bluetooth module, then communicates with the training program running on a computer. The program then handles various metrics in assessing the athletes' performances. A more detailed block diagram explanation and other justifications for the design choices will be elaborated in the next section.

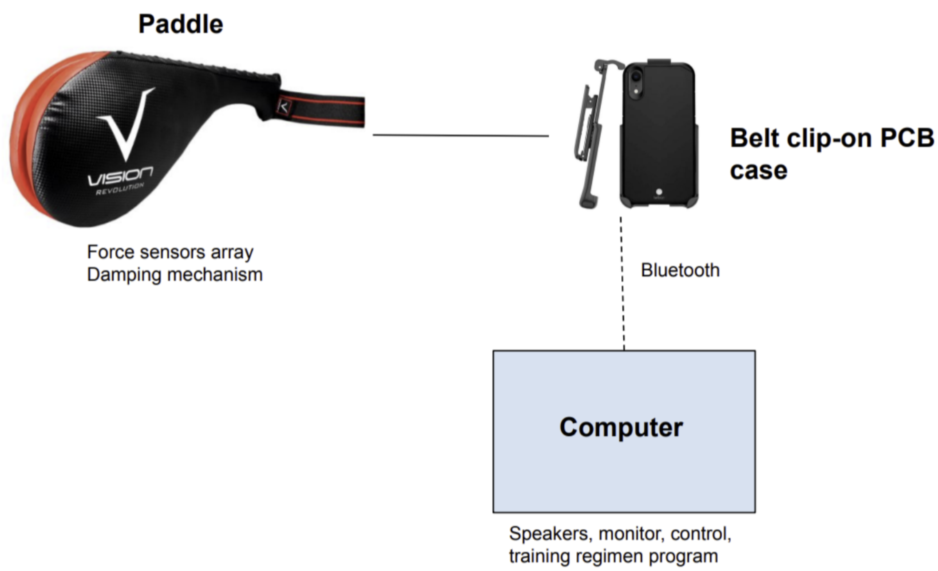

Figure 2: Visual aid for the design of the prototype

The performance requirements for our project since our design document, we made a few block-level changes, the most notable ones being our power supply and our display/computer subsystem. The original design intended to use a 9V rectangle alkaline battery. For the final design, the 9V battery was replaced with four AA cylindrical alkaline batteries, which totaled to roughly 6V. The reason for this change was that the 9V overloaded the PCB, and after a couple days of testing and use, it started to burn the circuits. The 6V total power supply ended up being more reliable and safe for long term use without making any sacrifices to power.

The second change was the entirety of the display/computer subsystem. We initially planned to use a second microcontroller STM32 to handle the display/computer subsystem part of the design, alongside the existing ESP32 microcontroller. However, we later determined that using a modern computer (windows or mac) would handle the project more efficiently. The two biggest advantages for using a computer instead of a standalone microcontroller were the ability to develop a more elaborate training regimen program and the more streamline communication with the ESP32.

High Level Requirements

1. Paddle shall pair and maintain a BLE link, at a greater than 1m distance for a minimum of 5 minutes without dropping or being unable to send packets to maintain functionality.
2. On a single charge, the paddle should maintain connection and send data for greater than 30 minutes with no MCU brown-outs, and no mechanical failures (e.g. sensors breaking)
3. Strikes to the paddle should be consistently measured. Accurate strikes, in similar locations with similar holding should be within 20% force measured. For reaction speed, the paddle will show reaction speeds within 50ms of each other for same speed strikes.

2 Design

2.1 Design Procedure

Power Initially, we chose a 9V battery to power our system, since it would be compact, and our system was built to handle up to a 22V source. We tested with up to 10V and everything worked fine, however when testing with a physical 9V block battery instead of the bench supply, our pcb was burned. Due to this, we switched to a lower voltage source, four AA 1.5V batteries in series, to provide a consistent 6V. We then step the 6V down to 3.3V to supply our ESP32 which requires 3.3V. Then we step up the 3.3V to 5V to power our flexiforce resistors. There were a couple alternatives we could've tried but ruled out. We could have stepped down the 6V to 5V directly, instead of stepping it down and then boosting it, however that would have required a more complex design that didn't make sense on our board, so for simplicity sake we simply boosted the 3.3 to 5V.

Control We chose the esp32-s3 Wroom 1, as it was powerful enough for us to continue to poll the sensors without drawing too much power. Another advantage was that it has built-in bluetooth connectivity. This was beneficial for our compact pcb design, so we didn't have to incorporate a separate bluetooth module. We considered having a more powerful MCU like an stm32 H7, however we decided that was overkill since we would be handling most of the complex processing off of the MCU anyways. It also would've drawn more power, been harder to solder, and required us to integrate a separate bluetooth module. In terms of programming the esp, we added the necessary pieces to handle UART connectivity. We had a 6 pin port which connected to our esp, after passing through our two buttons necessary to reset the esp and put it into download mode. We were then able to program it simply using a usb-uart converted and the Arduino IDE. We could have chosen to do a direct USB connection, however it was recommended that we use the UART connection instead as that was more robust, and the usb connections are prone to failure. Considering this design would need to handle a certain amount of stress, we went with the most robust solution.

Sensing We chose to do a two sensor array, using two flexiforce 0-100lb force sensing resistors. Each sensor is flexible and long enough for us to put inside the paddle, and have the actual connections closer to the holder's hand, rather than the place of impact. With an array of sensors we were able to measure force at separate areas on the paddle, to give an overall force and accuracy. We incorporated a few different dampening measures to make sure the sensor wasn't hit with too much force. One such measure was simple foam dampening. Then we also had cardboard on top of the foam, with a smaller piece of cardboard to ensure the force actually hits the sensor head properly. Finally, there was the actual dampening built into the paddle to protect the kicker's foot. These sensors were then connected through an op amp and potentiometer each. The reasoning for this is then we can adjust the sensor's sensitivity after it is all integrated into the paddle. This also allows for adjustment of the sensitivity based on the kicker. So stronger kickers can have the sensitivity lowered, and weaker kickers can have it raised. This was all then connected to the esp ports.

Display and Computer We originally planned on using a separate pcb for a control module to handle the processing and have a simple display just for reading force, however we decided to scrap that and go with processing it on the computer instead. This allowed for us to do a few things such as handling multiple paddles concurrently, having mini games and training regimens, and many other functionalities that would not have been possible without using a computer. We have a python program that handles most of the heavy lifting, so that we are able to focus on just the sensor processing on the esp side. The computer program works on any computer so anyone can use it.

Major Equations:

$$V = I \times \frac{R_1}{R_2} \tag{1}$$

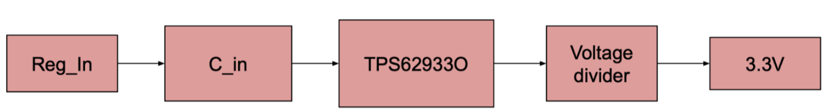

Figure 3: General Power Equation Visual

$$\text{Flexi Out} = \left(1 + \frac{R_{\text{pot}} + R_{\text{in}}}{R_s}\right) \times V_{\text{ref}} \tag{2}$$

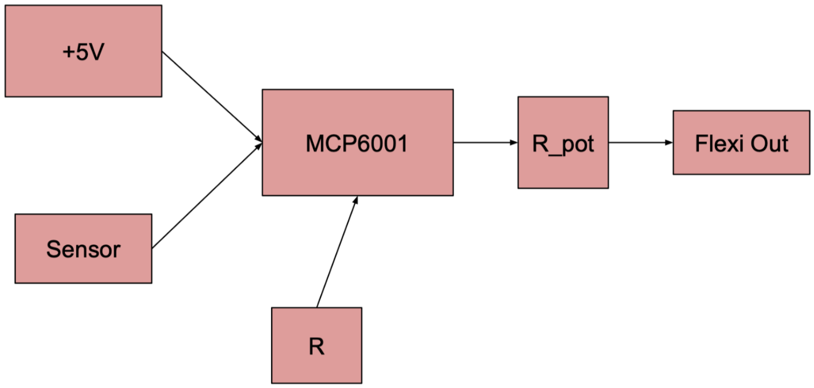

Figure 4: General Sensor Equation Visual

For boost converter mt3608:

$$V_{\text{out}} = V_{\text{ref}} \times \left(1 + \frac{R_1}{R_2}\right) \tag{3}$$

Equation for the dampening provided by the padding: The sensing area is a 0.375″ diameter circle. This gives us an area of 0.11045 in^2. We will have a pad of area 5 in^2 placed to distribute the force of the blows. $0.11045/5 = 0.022 = 2.2\%$ of the force is directed to the sensor itself. However this is in a perfect scenario where all of the force is distributed evenly, however in most practical scenarios this won't be the case. This is why we are using a 5in^2 1in thick piece of memory foam to help reduce the force even further. We can calculate the force reduced by the foam by treating it like a spring.

$$k = \frac{E \times A}{t} \tag{4}$$

Where: E = 30kPa (average compressive modulus for low-density memory foam) A = 5 in^2 = 0.00323 m^2 t = 1 in = 0.0254 m So, $k = \frac{30{,}000\ \text{Pa} \times 0.00323\ \text{m}^2}{0.0254\ \text{m}} = 3819$ N/m To calculate the force transmitted through we will use a linear spring model:

$$F = k \times t \tag{5}$$

$F = 3819\ \text{N/m} \times 0.0254\ \text{m} = 97\ \text{N} = 21.8\ \text{lbs}$

2.2 Design Details

Present detailed design with diagrams and component values:

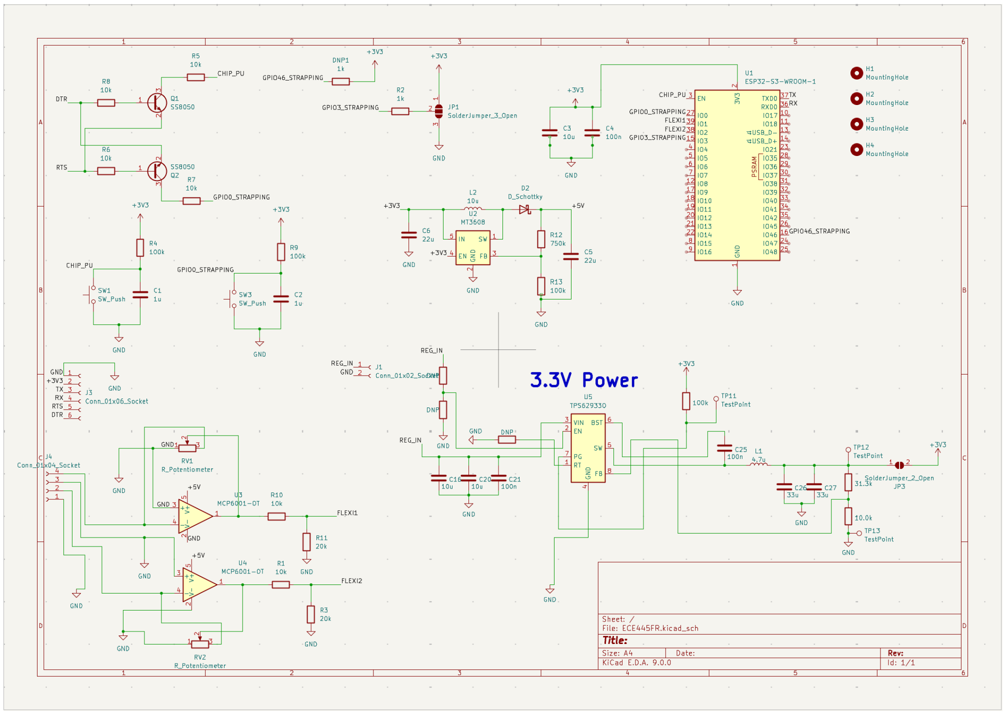

Figure 5: Schematic of the design

Power Here we use two 10μF capacitors and one 100nF capacitor for C_{in}. We use the 31.3kΩ and 10kΩ resistors for our voltage divider:

$$V = Vin \times \frac{31.3\text{k}\Omega}{10\text{k}\Omega} \tag{6}$$

which gives us 3.3V when we have a current just above 1A.

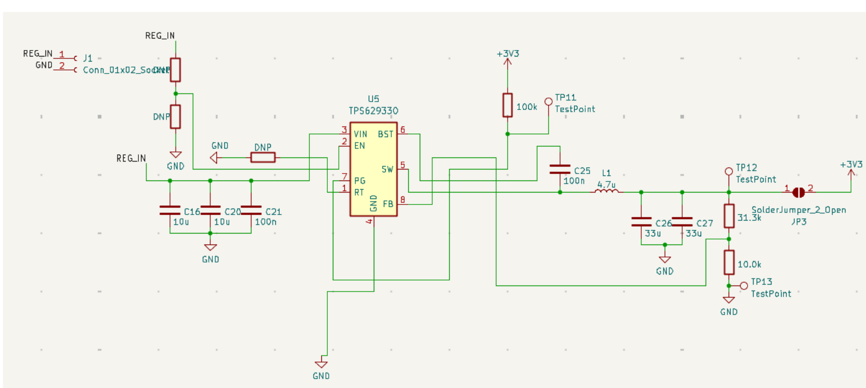

Figure 6: Detailed Power Circuit 1

For the boost converter:

$$V_{\text{out}} = V_{\text{ref}} \times \left(1 + \frac{R_1}{R_2}\right) \tag{7}$$

Where V_{ref} is 0.6V, we use our 750kΩ and 100kΩ resistors to give us an output voltage of 5V. $(0.6V \times (1 + 750k\Omega/100k\Omega) = 0.6V \times (1 + 7.5) = 0.6V \times 8.5 = 5.1V)$.

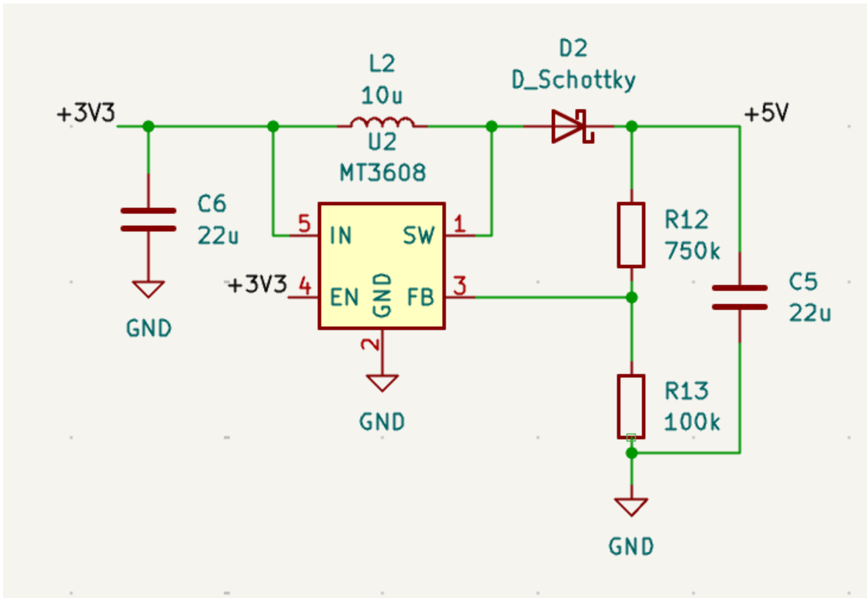

Figure 7: Detailed Power Circuit 2

Sensing

$$\text{Flexi Out} = \left(1 + \frac{R_{\text{pot}} + 10\text{k}\Omega}{20\text{k}\Omega}\right) \times 5\text{V} \tag{8}$$

This gives us an adjustable output voltage based on what we set for our potentiometer.

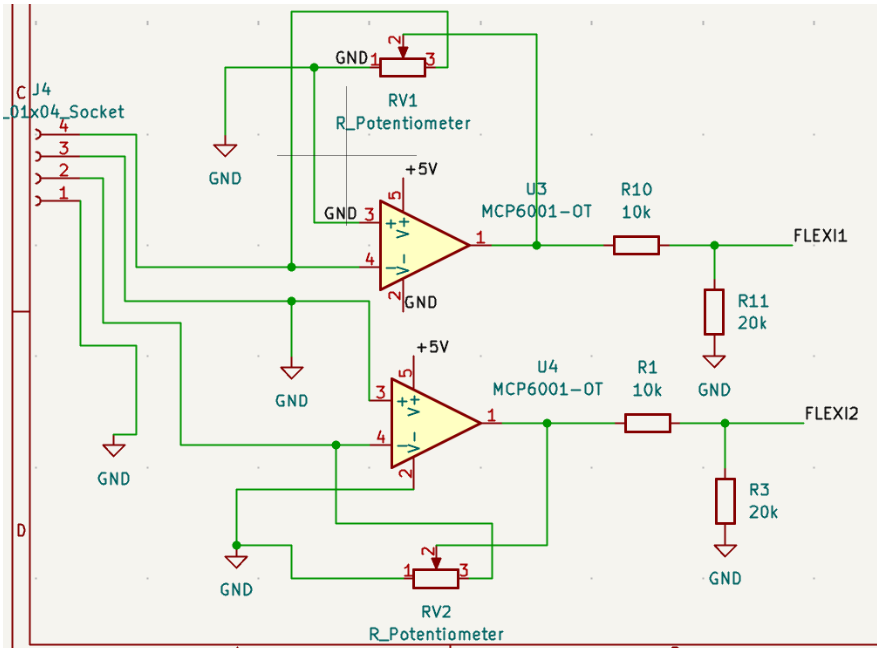

Figure 8: Detailed Sensor Circuit

Control The ESP32-S3 Wroom 1 serves as the main microcontroller. It handles polling data from the force sensors via its ADC ports after the signals have been conditioned by the op-amp circuits. The ESP32 then transmits this data over Bluetooth Low Energy (BLE) to the connected computer running the training program. Program flashing and debugging are handled via a UART interface, with physical buttons for reset and bootloader mode.

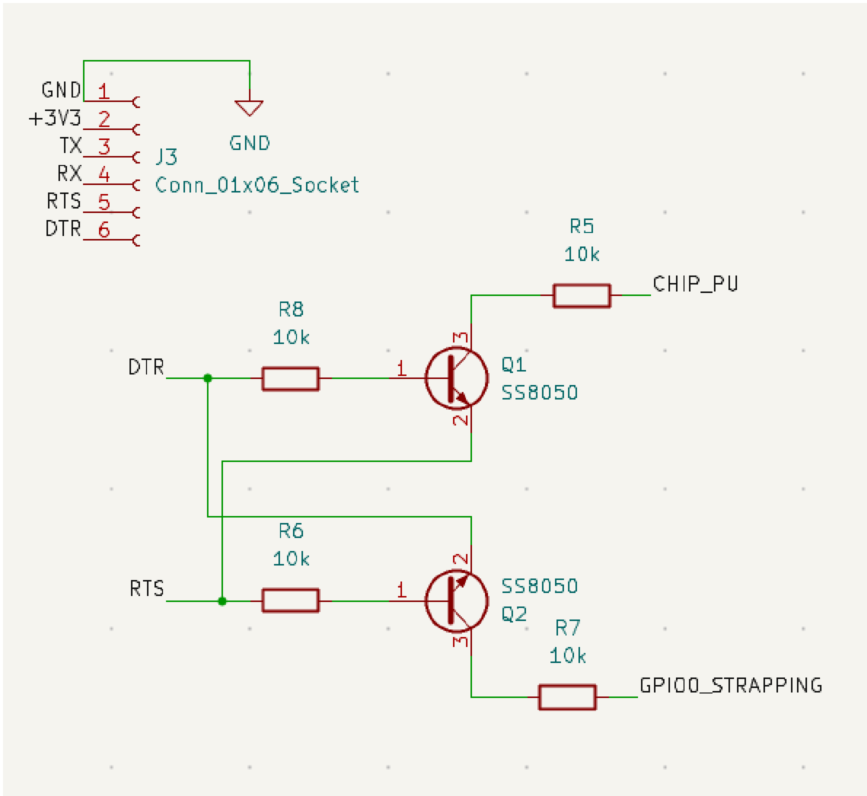

Figure 9: Detailed UART Interface Circuit

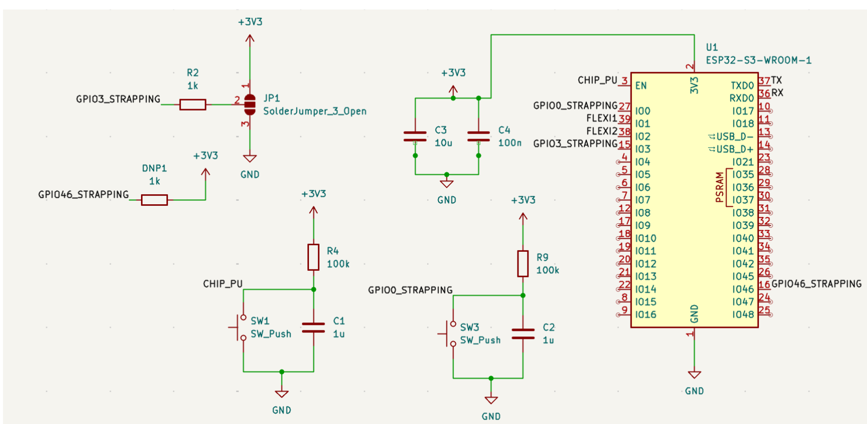

Figure 10: Detailed Control Circuit

3 Verification

Discuss testing of the completed project and its major blocks:

3.1 Requirements and Verifications Discussion

3.1.1 Power R/V

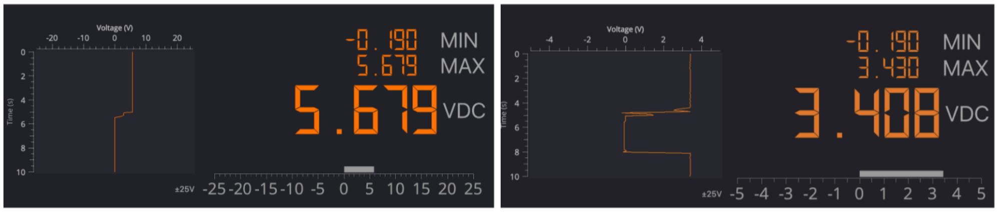

Figure 11: Power System Voltage Graph

One of the most important requirements that must be met is our power system. Under normal use, we had to guarantee that our batteries lasted longer than 30 minutes, and ideally for roughly around an hour, since regular training sessions last around an hour. Figure 10a shows that our main power supply for four AA batteries were able to provide around 6V. The readings are currently 5.679V since the same set of batteries were used for a few days, which is more than enough to verify our requirements. The second requirement for power is that the ESP32 should be getting at least 3.2V and at most 3.6V. Figure 10b confirms that our 6V power supply successfully stepped down to that operating voltage for the ESP32.

3.1.2 Display/Computer Subsystem R/V

The paddle, which is handled by the ESP32, connects via bluetooth to the computer running the program in under 5 seconds. Every time we connected the ESP32 to the computer for testing, we timed it so that connection was made in a timely manner of under 5 seconds. We also ensured that other computers were able to connect to the same ESP32 that is already connected to prevent interferences and errors in communication. Lastly, we followed our philosophy of making the design accessible to everyone by ensuring that our program was runnable in almost all modern computers/devices. We verified it by testing on multiple windows and mac computers.

3.1.3 Sensing R/V

Our final R/V table lists four crucial components of our design to be an effective design. The first requirement was that the force readings are consistent. We ensured that, by utilizing different labeled weights, that the paddle resting on the floor was able to read a consistent force reading within a 5 percent error. Furthermore, we verified that the sensors were able to identify different forces relative to each other by using lighter objects and heavier objects. Our goal was not reading perfectly accurate readings of the force of the kicks, due to many complications in force being lost to the environment, but instead getting consistent, relative results. The second requirement states that the force sensors don't pick up extraneous noise other than the actual strikes themselves. Due to the sensors already being activated by the nature of how it is set up inside the paddles with the damping foams, it was picking up some force by default. We set a threshold for that noise so that our force measurements strictly reflected the forces from the strikes. This was verified by observing that no noise was picked up when the paddle was resting in the holder's hands. Our third requirement was more specific to the speed drill training regimen where the force sensor timing was accurate within 50ms. We accounted for the latency in communication of the ESP32 with the computer via bluetooth to ensure that the force readings were accurately reported based on the true reaction speed of the athlete. This was verified by intentionally hitting the paddle with different timings. The final requirement was that the accuracy measure is sensible. Our accuracy measurement was rated by taking the ratio of the forces read by the two sensors, and this was verified by intentionally holding the weights from before strictly to one side of the paddle. We observed that the accuracy calculations were most of the times under 50 percent, which is the correct behavior. When the weight was evenly distributed among both sensors, the accuracy was closer to 90

4 Costs

Labor cost estimates should use the following formula for each partner: ideal salary (hourly rate) $\times$ actual hours spent $\times$ 2.5

4.1 Labor

We are estimating a salary of \$30/hour. We are estimating roughly 112 man hours. 8 hours per week for 7 weeks, for two people, brings us to 112 hours. Labor: \$30/hour $\times$ 2.5 $\times$ 112 hours to complete = \$8400

4.2 Materials (for one iteration electronic paddle)

Description	Manufacturer	Part #	Quantity	Cost/u
Cable and pin connectors	Molex	WM1350X-ND	3	$2
Capacitor	Samsung electronics, TDK Corporation,	1276-7091-1-ND, 445-8238-1-ND	20	$0.5-2
Operational Amplifier	Microchip Technology	MCP6001T-I/OTCT-ND	2	$1.20
Buck Converter	Texas Instruments	TPS62933ODLR	1	$2.08
Inductor	Würth Elektronik	732-74408063004CT-ND	2	$5.52
1M Ohm Potentiometer	Bourns Inc.	3214W-1-105ECT-ND	2	$2.54
MCU	Espressif	ESP32-S3-WROOM	1	$16
Boost switching regulator IC	Diode Incorporated	AP3012KTR-G1DICT-ND	1	$1.34
Force Sensors	FlexiForce	3102_0	2	$22.75
Schottky Diode	Onsemi	RB521S30T1GOSCT-ND	1	~$3
BJT Transistor	Comchip Technology	SS8050-G	1	$0.96
Resistors	Stackpole Electronics Inc		20	$0.2-0.5
Phone Case (PCB enclosure)	Rome Tech store	Samsung Galaxy S25 Case with Belt Clip Holster & Kickstand	1	$14.99
PCB	PCBway	Custom Manufactured	10	$2

Figure 12: Materials Cost Breakdown

5 Conclusions

Overall, our electronic martial arts paddle design is fully functional, complying with our initial expectations. When an athlete strikes the paddle, a force measurement and the strike's accuracy is displayed on the training program through the computer screen. The paddle subsystem and computer effectively communicates via bluetooth, with very minimal latency. Other training modes are available, such as kicking school, which grades the athletes' kicks based on a letter grade, and speed drill, which tests the reaction speed of the athlete by playing a "beep" sound.

To improve on the future design, we would like to list a few recommendations. For the number of usable paddles, we had originally intended to operate with two separate paddles so that multiple athletes can train together or so that one athlete can train with multiple paddles at a time. Unfortunately, our first PCB had burned out with a 9V battery, so we were not able to incorporate it into our design. Regardless, knowing that we already have one working paddle, it will be fairly simple to add more paddles for a more intricate training regimen program. With respect to the training program, many improvements can be made to the program itself, including a system to keep track of statistics or high scores for every athlete. Finally, we have two ideas for improving the quality of life of the paddle subsystem itself. The current design of the paddle is like any other paddle on the market right now. We can further modify the current design by cutting up the paddle into different sections for where each force sensor is placed so that the sensors read a more isolated reading. Moreover, we can further minimize the physical size of the PCB with more efficient placement of the components to fit it directly on the handle of the paddle. This way, it eliminates the need for wires running to a PCB enclosing clipped onto your belt.

We believe that the broader impacts the design will bring is very clear. Globally, we believe that more athletes will be able to train at a standard closer to a real tournament and Olympic setting, without having to rely blindly on subjective intuition and instead getting quantitative metrics and visualizations for their performances. Whereas official fighting gear can be around $3000, our electronic martial arts paddles provide a similar quality of training for a thirtieth of the price. We determined that our design is sufficiently effective for everyday TKD training.

Ethical Considerations

We will adhere to IEEE [1] and ACM Codes of Ethics [2], ensuring our work follows best practices. A clear reporting channel and regular internal reviews will be maintained to identify and address any ethical issues. All data handling and communications will remain transparent and aligned with industry standards.

Honesty and Transparency We will accurately communicate the prototype's capabilities and limitations, including any assumptions or uncertainties in our testing and design. This aligns with ACM's standards of honesty and trust.

Safety Considerations

Usage Guidelines Beginners should use the prototype only under the supervision of experienced Taekwondo athletes. With over 10 years of experience each, Liam and Alex are qualified to ensure safe usage.

Hardware Safety Only components that meet electrical safety standards will be used. Proper precautions, such as anti-static tools and surfaces, will be implemented during development.

Physical Safety The paddles will be designed to avoid overloading or placing components in striking areas. The structure will undergo impact and durability testing, and athlete feedback will guide ergonomic improvements to minimize injury risk.

6 References

References

[1] IEEE. "IEEE Code of Ethics." (2020), [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 03/03/2025).

[2] Association for Computing Machinery. "ACM Code of Ethics and Professional Conduct." (2018), [Online]. Available: https://www.acm.org/code-of-ethics (visited on 03/03/2025).

[3] STMicroelectronics. "STM32H7R7/I8T6 Arm Cortex-M7 MCU." Access to the specific page for STM32H7R7I8T6 might vary, linked to similar series page. (), [Online]. Available: https://www.st.com/en/microcontrollers-microprocessors/stm32h7r7i8.html (visited on 03/03/2025).

[4] Monolithic Power Systems. "MP1584 - 3A, 28V, 1.5MHz Step-Down Converter." (), [Online]. Available: https://www.monolithicpower.com/en/mp1584.html (visited on 03/03/2025).

[5] Diodes Incorporated. "AP2112K-3.3TRG1 - LDO Regulator Pos 3.3V 0.6A 5-Pin SOT-25 T/R." (), [Online]. Available: https://www.digikey.com/en/products/detail/diodes-incorporated/AP2112K-3-3TRG1/4470746 (visited on 03/03/2025).

[6] D. Corcoran, B. Green, J. Northey, *et al.*, "Impact Force and Velocities for Kicking Strikes in Combat Sports: A Literature Review," *Sports*, vol. 12, no. 3, p. 74, Mar. 2024, Published: 6 March 2024. DOI: 10.3390/sports12030074. [Online]. Available: https://doi.org/10.3390/sports12030074.

[7] Tekscan. "FlexiForce extsuperscript extregistered Force Sensors." The URL provided by user "https://www.flexiforce.com/us/en" redirects to Tekscan, the manufacturer. (), [Online]. Available: https://www.tekscan.com/products-solutions/force-sensors (visited on 03/03/2025).

[8] Phidgets Inc. "Phidgets - USB Sensors and Controllers." (), [Online]. Available: https://www.phidgets.com/ (visited on 03/03/2025).

[9] Aerosemi. "MT3608 1.2MHz, 2A Step-up Converter Datasheet." (), [Online]. Available: https : / / www . olimex . com / Products / Breadboarding / BB - PWR - 3608 / resources/MT3608.pdf (visited on 03/03/2025).

R/V table:

Power:

Requirement	**Verification**	**Pass/Fail**
Under normal use, the batteries will last > 30 mins	Have paddle powered on and connected for 30 mins	Pass if batteries last over 30 mins
The 6V power will be converted to ~3.3V to supply the esp32 and will remain consistent under load.	Show that the esp is powered with 3.3V and that it is converting from the 6V power supply.	Pass if power to esp is within 0.2V of 3.3V to remain in safe range.

Display/Computer Subsystem:

Requirement	**Verification**	**Pass/Fail**
Paddle will connect to computer in under 5 seconds	Show that from clicking the button to when it is connected takes less than 5 seconds.	Pass if able to connect in under ~5 seconds.
Paddle only connects to one computer at a time	Show that the paddle rejects connecting to two computers at once	Pass if seconds computer can't connect while one computer is currently connected
Should be able to run on multiple devices	- Run main.py on macOS - Run main.py on windows OS	- Program runs successfully

Figure 13: Requirements and Verification Table (Part 1)

Sensing:

Requirements	Verification	Pass/Fail
Force Sensor readings are consistent	- Intentionally press onto to one side of the paddle - Press lightly on the paddle, and press relatively harder	- Force sensor should read a higher measurement for the sensor corresponding to that side - Force readings should be comparably different
Force sensor picks up no noise	- Holding the paddle without any kicks or other interference	- Minimal force readings on the program
Force sensor timing is accurate within 50ms	- Hit paddle at different times to show different timings	- Hitting paddle should show different times at different reaction speeds
Accuracy calculations are sensible	- When one side of the paddle is pressed, accuracy is under 50% - When both sides (both sensors) of the paddle is pressed simultaneously, accuracy is above 80%	- Our accuracy calculation allows us to verify that both sensors must exert a similar force to result in a high accuracy. It was a pass.

Figure 14: Requirements and Verification Table (Part 2)