TECHIN 515A

TECHIN515 Lab 4 - Magic Wand

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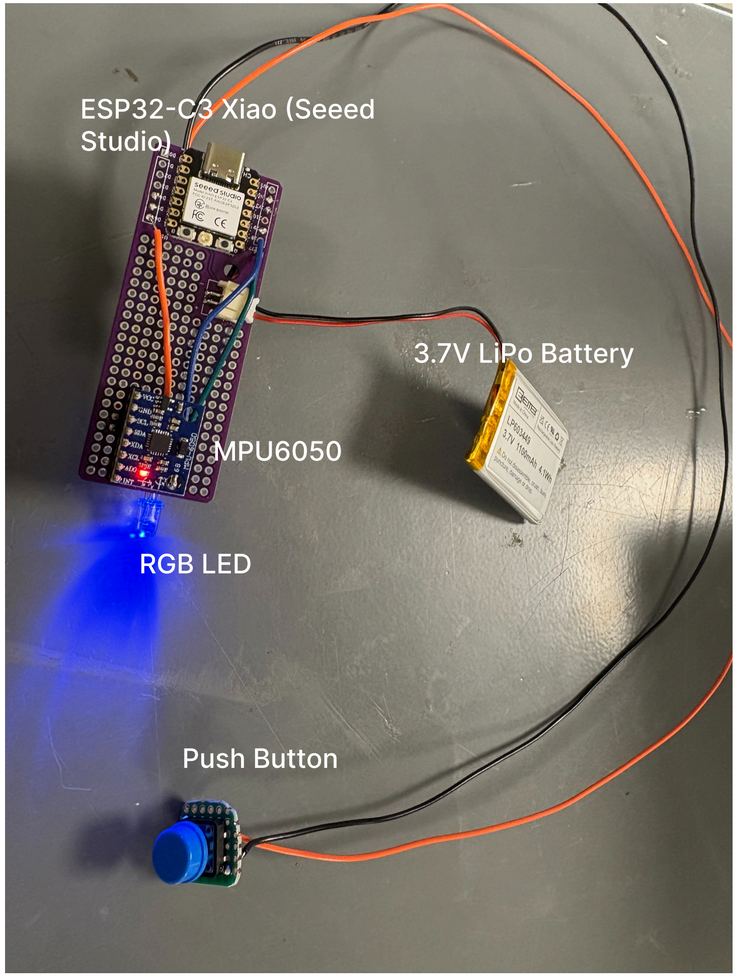
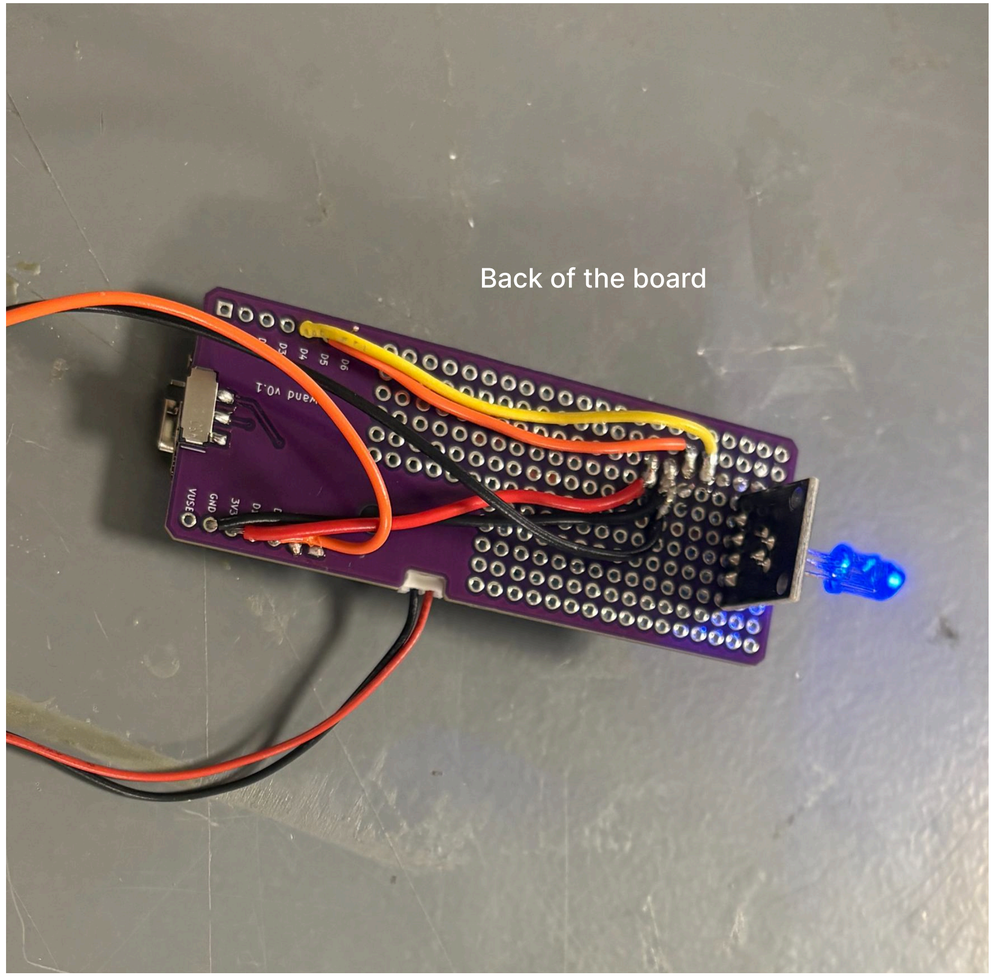
May 19, 2025

Pictures of hardware setup and connections





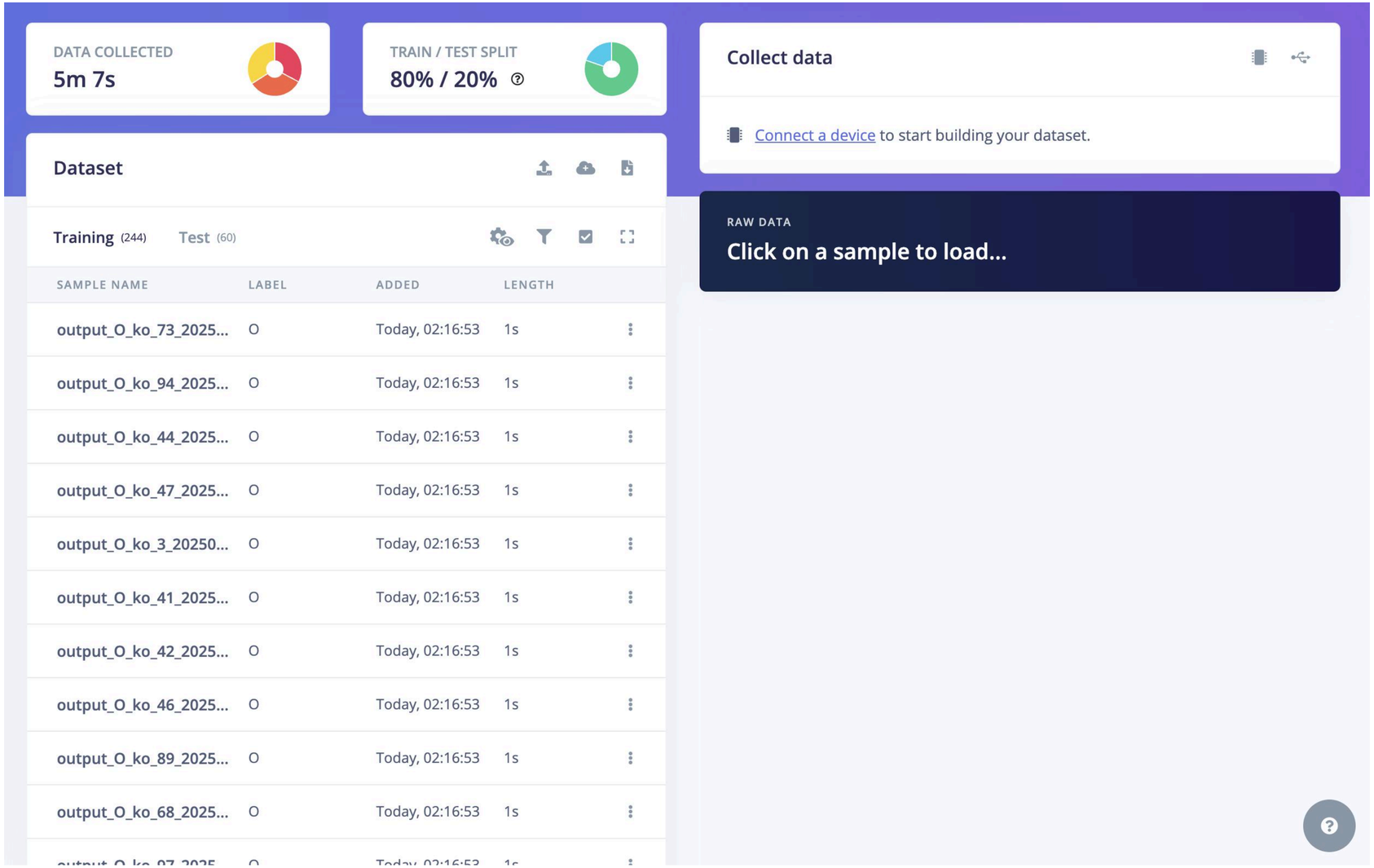
Data collection process and results

```
Capture started...
Saved 101 samples to data/O/output_O_ko_97_20250519_020824.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_98_20250519_020826.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_99_20250519_020828.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_100_20250519_020830.csv
^C
Exiting...
Serial connection closed
(.venv) (base) linjunzhang@Linjuns-MacBook-Pro-2 gesture_capture % python process_gesture_data.py --gesture "V" --person "ko" --port /dev/
cu.usbmodem101

Created directory: data/V
Connecting to ESP32 on /dev/cu.usbmodem101 at 115200 baud...
Connected! Waiting for gesture data...
Press Ctrl+C to exit
Send 'o' to start capture (will automatically stop after 1 second)
Capture started...
Saved 101 samples to data/V/output_V_ko_1_20250519_021028.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_2_20250519_021031.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_3_20250519_021033.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_4_20250519_021035.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_5_20250519_021037.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_6_20250519_021039.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_7_20250519_021041.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_8_20250519_021043.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_9_20250519_021044.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_10_20250519_021046.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_11_20250519_021048.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_12_20250519_021049.csv
Capture started...
Saved 101 samples to data/V/output_V_ko_13_20250519_021051.csv
```

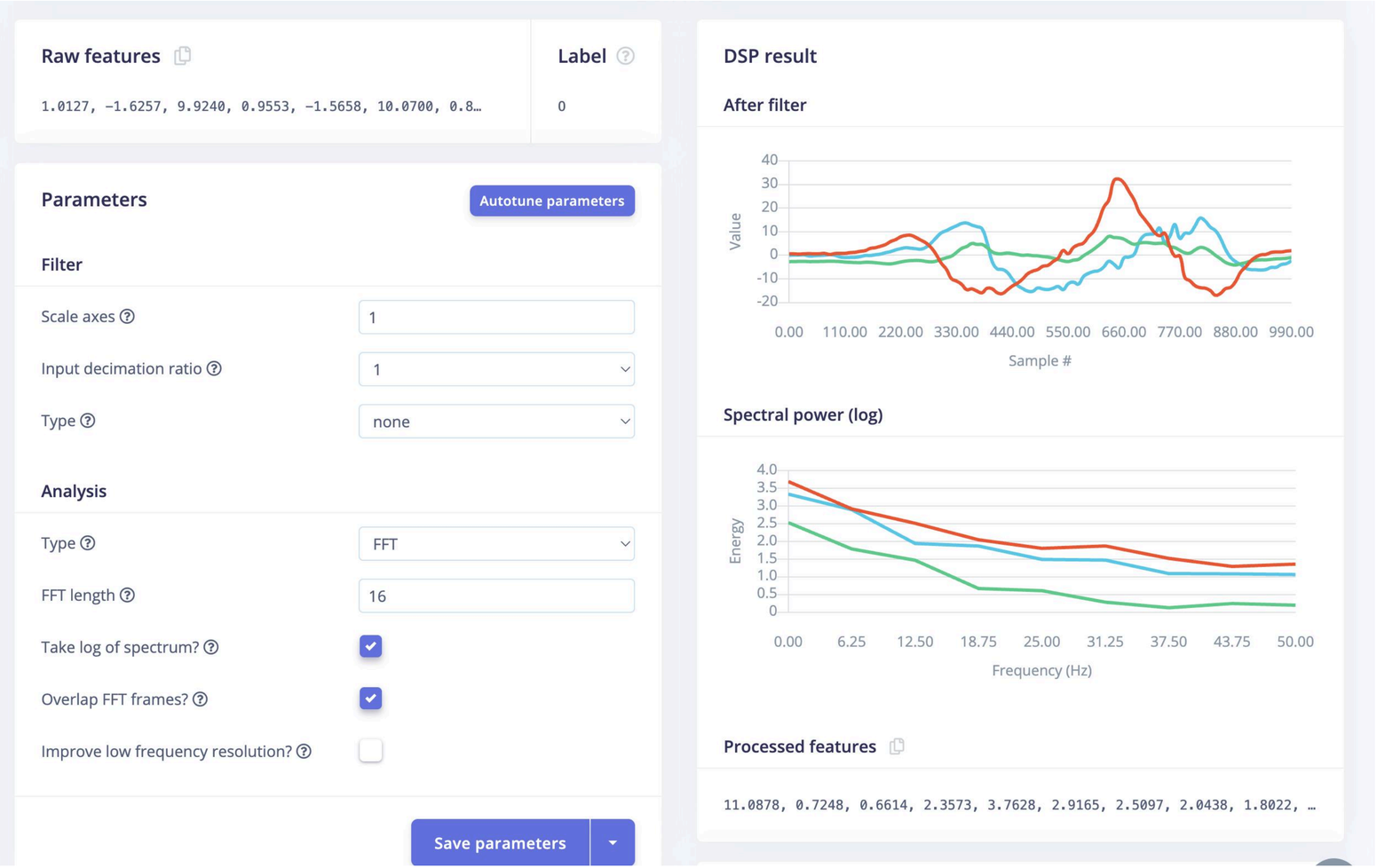
```
(.venv) (base) linjunzhang@Linjuns-MacBook-Pro-2 gesture_capture % python process_gesture_data.py --gesture "Z" --person "ko" --port /dev/
cu.usbmodem101

Connecting to ESP32 on /dev/cu.usbmodem101 at 115200 baud...
Connected! Waiting for gesture data...
Press Ctrl+C to exit
Send 'o' to start capture (will automatically stop after 1 second)
Capture started...
Saved 101 samples to data/Z/output_Z_ko_1_20250519_014919.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_2_20250519_014932.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_3_20250519_014936.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_4_20250519_014939.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_5_20250519_014942.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_6_20250519_014948.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_7_20250519_014950.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_8_20250519_014953.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_9_20250519_014955.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_10_20250519_014958.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_11_20250519_015000.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_12_20250519_015003.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_13_20250519_015005.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_14_20250519_015007.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_15_20250519_015010.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_16_20250519_015012.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_17_20250519_015014.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_18_20250519_015017.csv
Capture started...
Saved 101 samples to data/Z/output_Z_ko_19_20250519_015019.csv
```

```
Created directory: data/O
Connecting to ESP32 on /dev/cu.usbmodem101 at 115200 baud...
Connected! Waiting for gesture data...
Press Ctrl+C to exit
Send 'o' to start capture (will automatically stop after 1 second)
Capture started...
Saved 101 samples to data/O/output_O_ko_1_20250519_020522.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_2_20250519_020527.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_3_20250519_020529.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_4_20250519_020531.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_5_20250519_020533.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_6_20250519_020535.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_7_20250519_020537.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_8_20250519_020539.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_9_20250519_020541.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_10_20250519_020543.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_11_20250519_020544.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_12_20250519_020546.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_13_20250519_020549.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_14_20250519_020551.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_15_20250519_020553.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_16_20250519_020555.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_17_20250519_020556.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_18_20250519_020558.csv
Capture started...
Saved 101 samples to data/O/output_O_ko_19_20250519_020600.csv
Capture started...
```

Data collection process and results

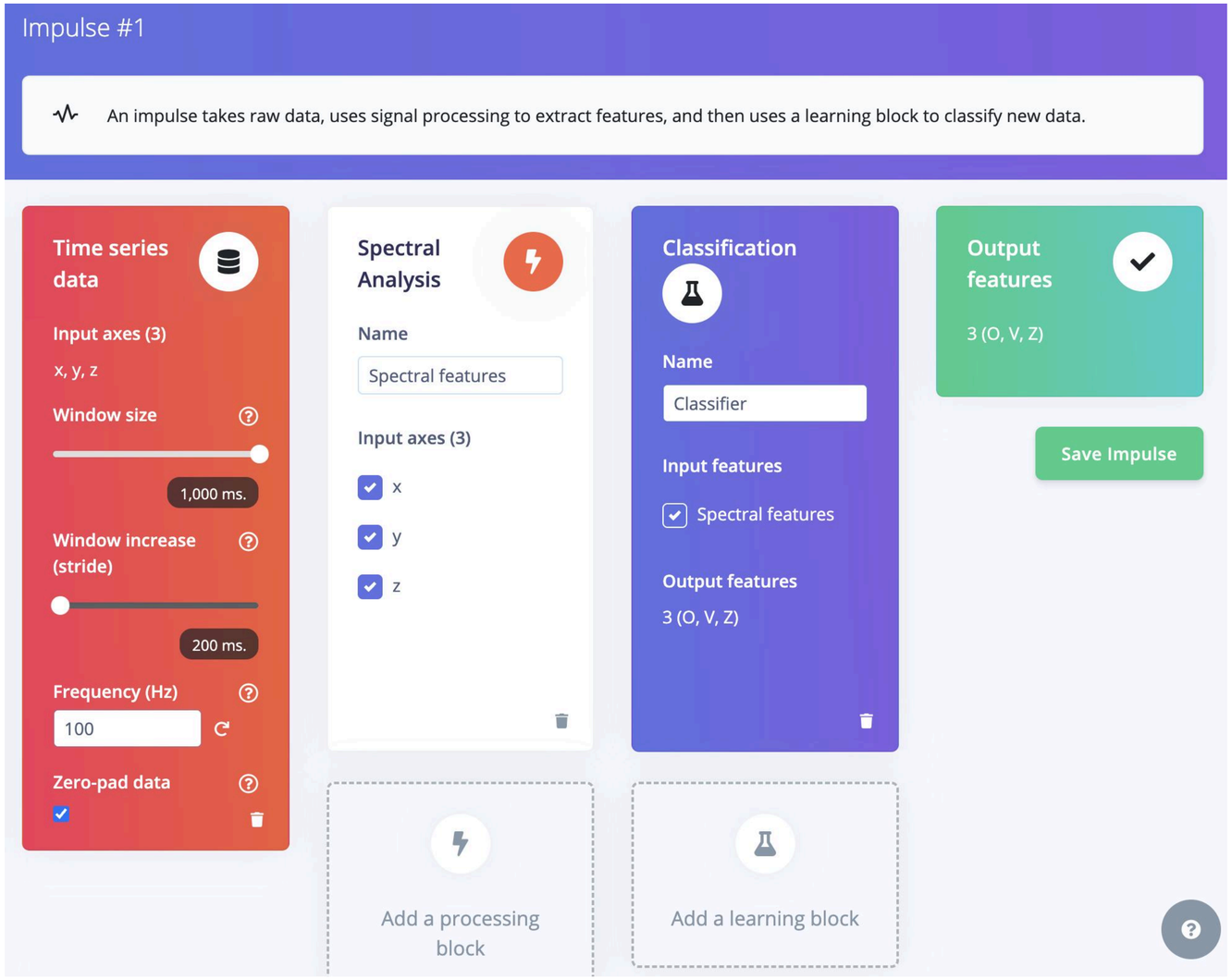


Edge Impulse Model Architecture and Optimization



I used the Spectral Analysis block in Edge Impulse to convert raw acceleration data into frequency-domain features. This is particularly effective for gesture recognition, as different hand movements produce distinct signal energy distributions across frequencies.

Edge Impulse Model Architecture and Optimization

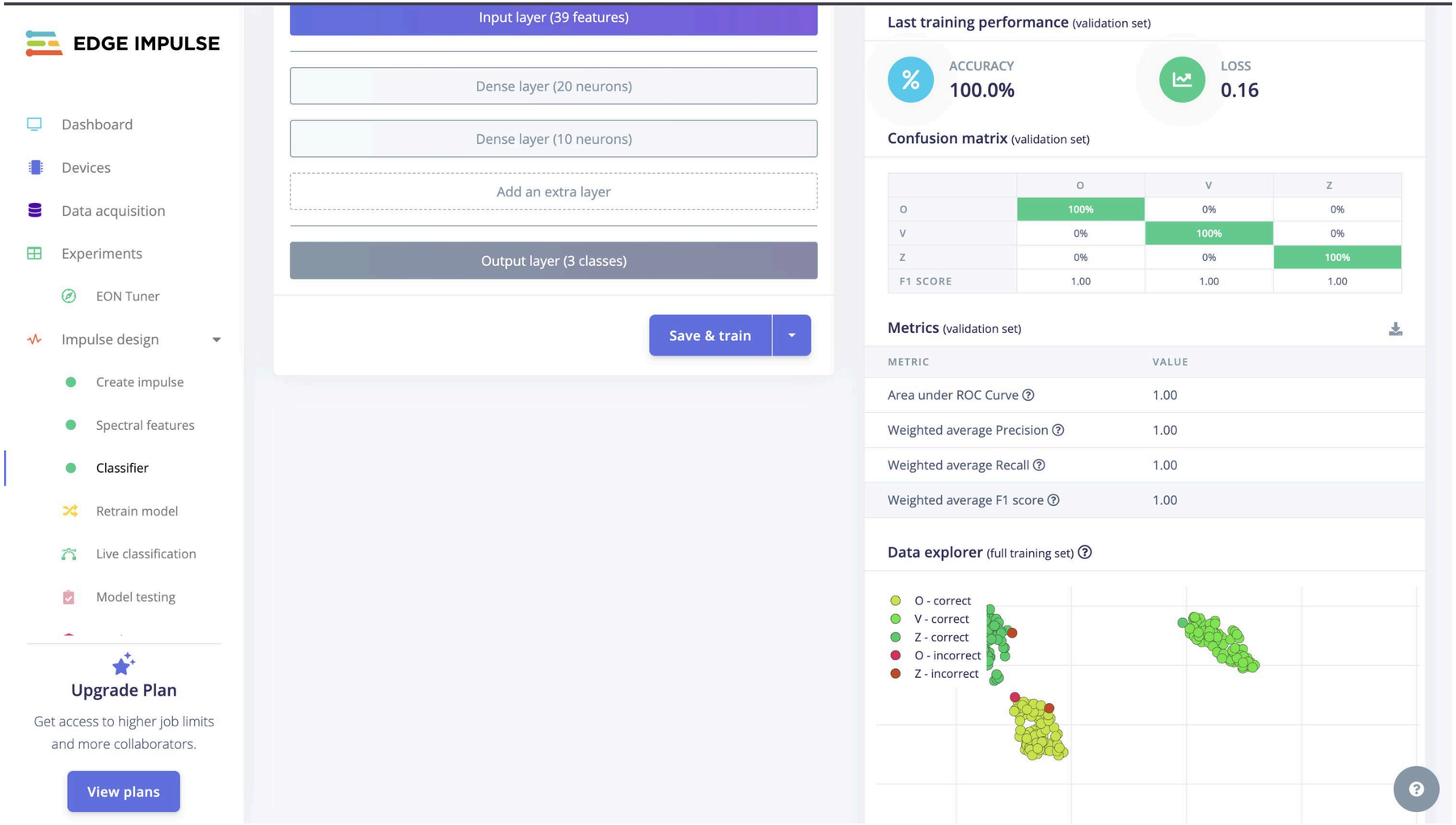


I designed and optimized the model in Edge Impulse using the following configuration:

- Input: Time-series data from MPU6050 (x, y, z) at 100Hz
- Window size: 1000ms (1 second gesture capture)
- Window increase: 200ms (stride)
- DSP block: Spectral Features (for frequency-domain analysis)
- Classifier: 2-layer dense neural network
- Output classes: 3 gesture labels — Z, O, and V

This structure effectively captured distinguishing features across the three gestures while maintaining low computational cost suitable for on-device inference.

Performance Analysis and Metrics



As shown in the confusion matrix below, the classifier correctly identified every gesture in the validation set. There were no misclassifications, and each label (Z, O, V) was predicted with perfect precision.
The Data Explorer visualization further confirms the separation between the three gesture classes. All samples clustered cleanly by class, with no significant overlap between gesture types.
This indicates that the model architecture — a 2-layer dense neural network with spectral features — was effective for this task. The performance is strong enough for real-time embedded deployment on the ESP32-C3 device.

Answers to Design Questions and Justifications

This system was designed for standalone use, so a physical button was used to trigger gesture capture instead of relying on serial input. A 1000ms window was selected to match the natural length of a hand gesture. Spectral Features were used as the DSP block to extract frequency-domain patterns, which are effective for distinguishing motion types.
The model architecture includes two dense layers (20 and 10 neurons), offering a balance between performance and deployment size. Quantization to int8 was applied to reduce memory usage and support ESP32 inference. During data collection, RGB LED feedback was added to confirm the current label, reducing the risk of mislabeling.
All decisions were made to ensure smooth real-time performance, minimize user error, and maintain compatibility with the ESP32-C3's limited resources.

Discussion

Discussion: Effect of Window Size

The window size determines how many time steps are included in each training sample. A larger window (e.g., 1000ms) generates fewer but more complete samples, which is helpful for capturing the full span of slower or complex gestures. However, it also increases the input vector size, which results in a larger number of neurons in the input layer and higher computational cost.

In this project, a 1000ms window with 100Hz sampling produced 300 features (x/y/z × 100). This size was chosen to balance coverage and model size, ensuring that even slow-changing patterns like circular “O” gestures are fully captured without truncation.

Discussion: Strategies to Improve Model Performance

1. Data Augmentation: Introduce slight noise, temporal shifts, or mirrored gestures to increase variability and reduce overfitting, especially since the dataset was collected from a single user.
2. Additional Sensor Channels: Incorporate gyroscope data from the MPU6050 in addition to accelerometer input. This would provide angular velocity information, improving gesture separability for similar movement paths.
3. (Optional) Ensemble or Hybrid Models: Combine a lightweight CNN with dense layers to extract both temporal and spatial patterns more effectively (though this may exceed MCU limits).

Demo Video Link

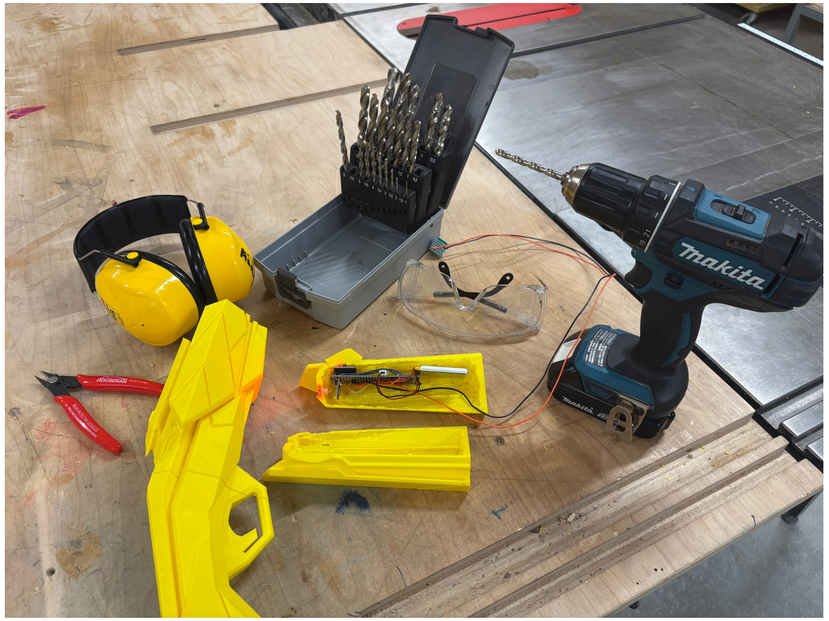
https://youtube.com/shorts/fXiE956W-jA?feature=share

Challenges Faced and Solutions

During development, one key challenge was serial port conflict between the Arduino IDE and the Python data collection script. Since both tools attempted to access the same USB port, switching between them often caused connection failures. This was resolved by explicitly closing the Serial Monitor before launching the Python script, and ensuring only one tool accessed the port at a time.

Another issue involved incorrect gesture labeling during data collection. Forgetting to update the gesture class before pressing the capture button led to mislabeled samples. To address this, we added RGB LED color feedback to indicate the active label in real time, reducing user error and improving dataset quality.

Enclosure and Battery



Enclosure and Battery