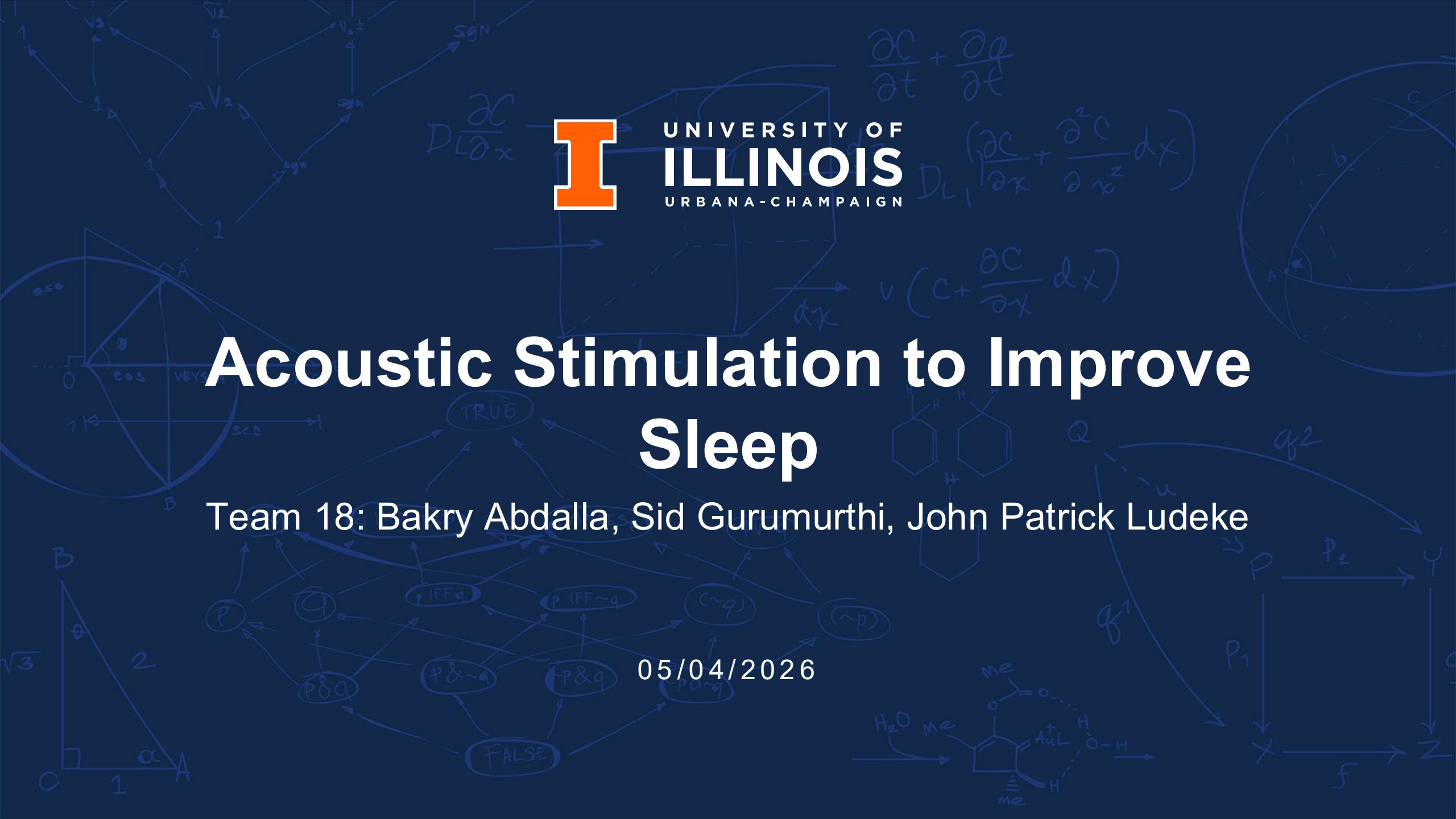
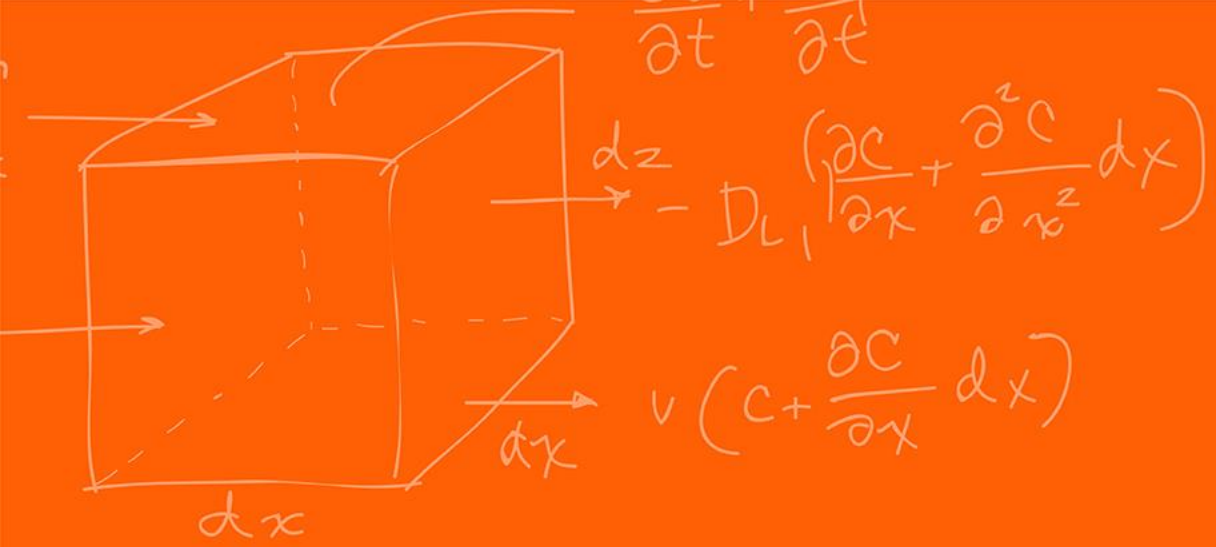


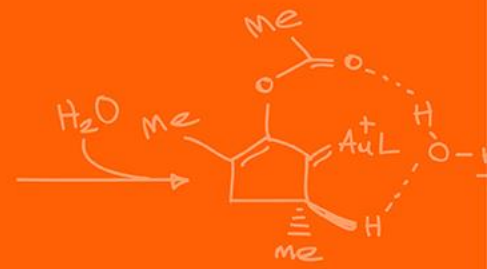
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Acoustic Stimulation to Improve Sleep

Team 18: Bakry Abdalla, Sid Gurumurthi, John Patrick Ludeke

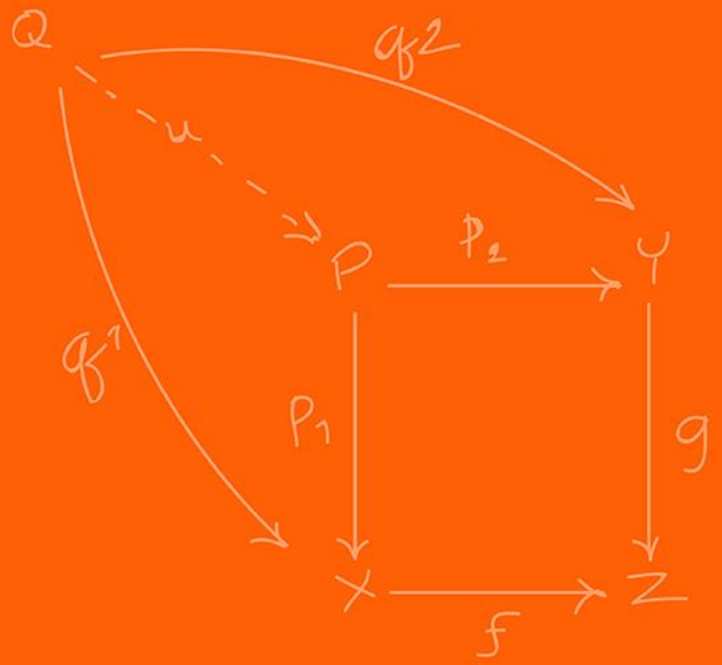
05/04/2026





Introduction

What's the problem?

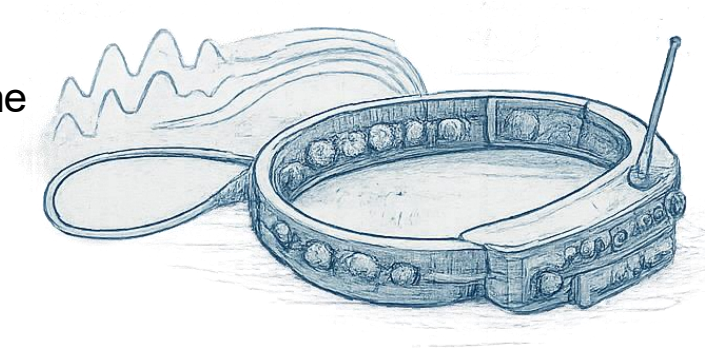


Slow Wave Sleep Decreases with Age and Sleep Disorders

- Average SWS = **4.4% ± 7.3%** of total sleep time
  - Younger (<55): **~9.1%** SWS
  - Older (≥55): **~2.1%** SWS

- Sleep apnea patients:
  - **~3.7%** SWS vs **~9.1%** in healthy individuals

- Reduced SWS is associated with:
  - Memory impairment, Diabetes risk, Hypertension, Psychiatric disorders, Immune dysfunction



Objective

How will we address this problem?

Objective

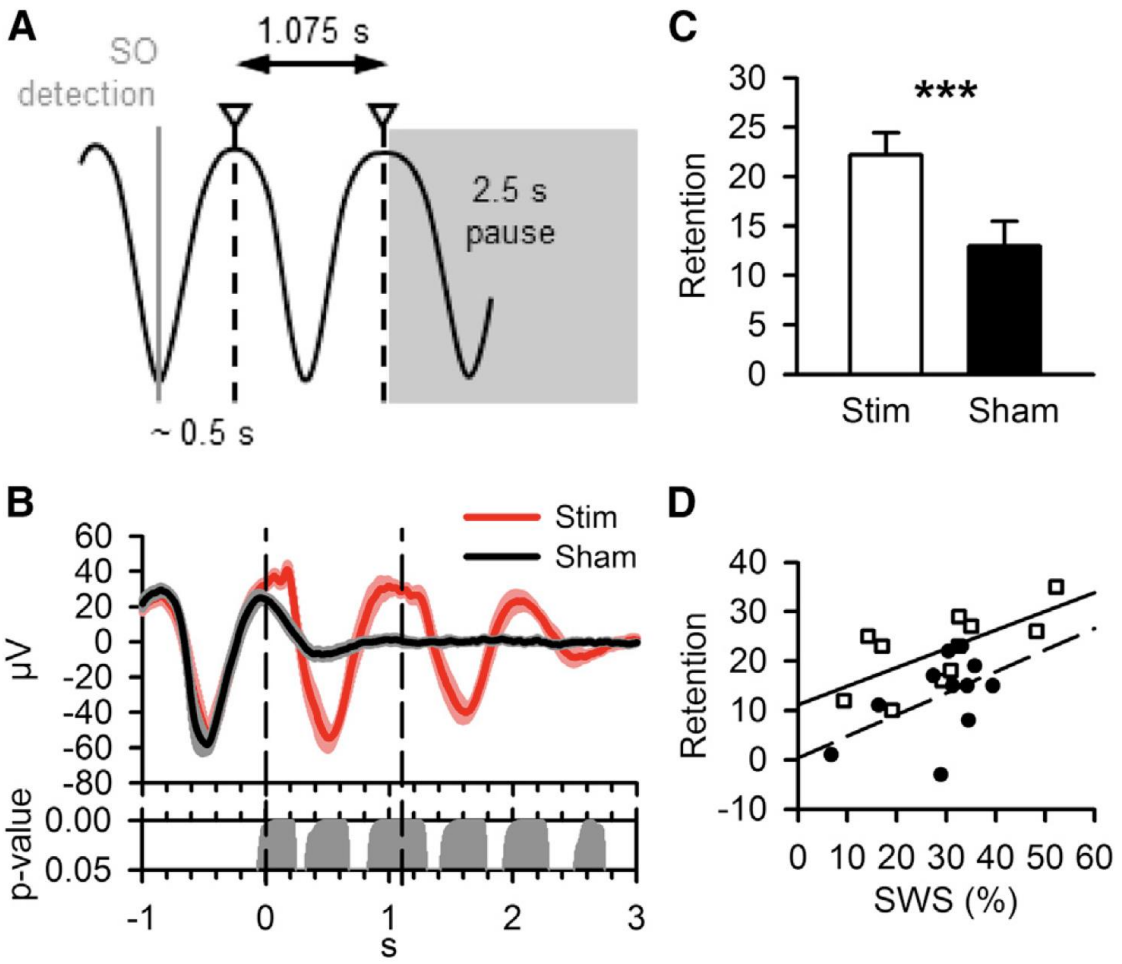
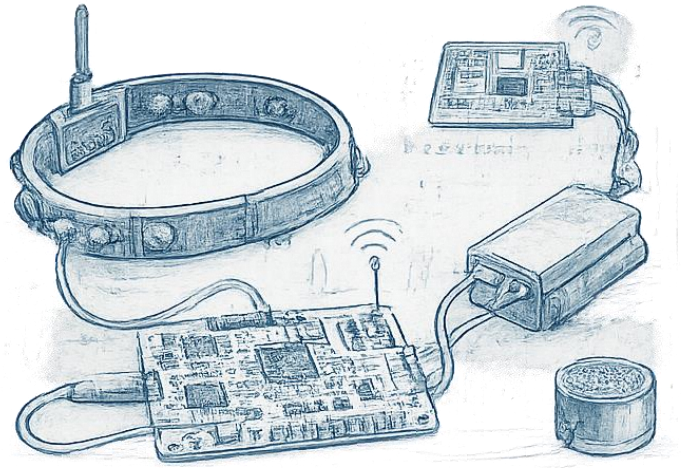


Figure 1. Closed-Loop Auditory Stimulation In-Phase with SO Up States Continues Oscillations

An EEG-Based Audio Stimulation Device

Closed-loop sleep stimulation system that:

- Acquires EEG via OpenBCI/Cyton,
- Performs accurate SWS classification
- delivers phase-aligned pink noise stimulation
- Low latency, safe output, and reliable overnight operation.



Initial & Final Design

What changed?

Initial Design

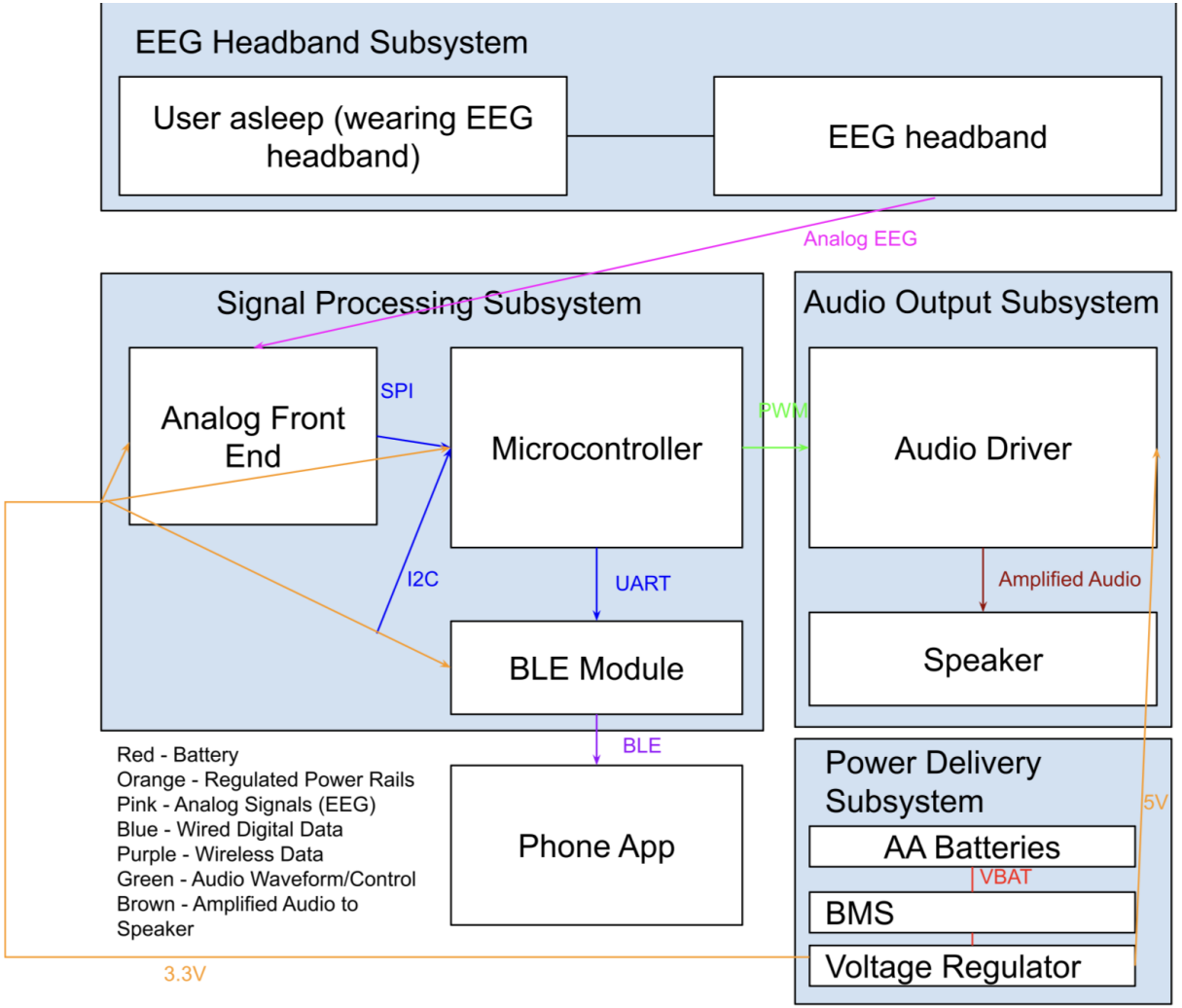


Figure 2. Initial Block Diagram

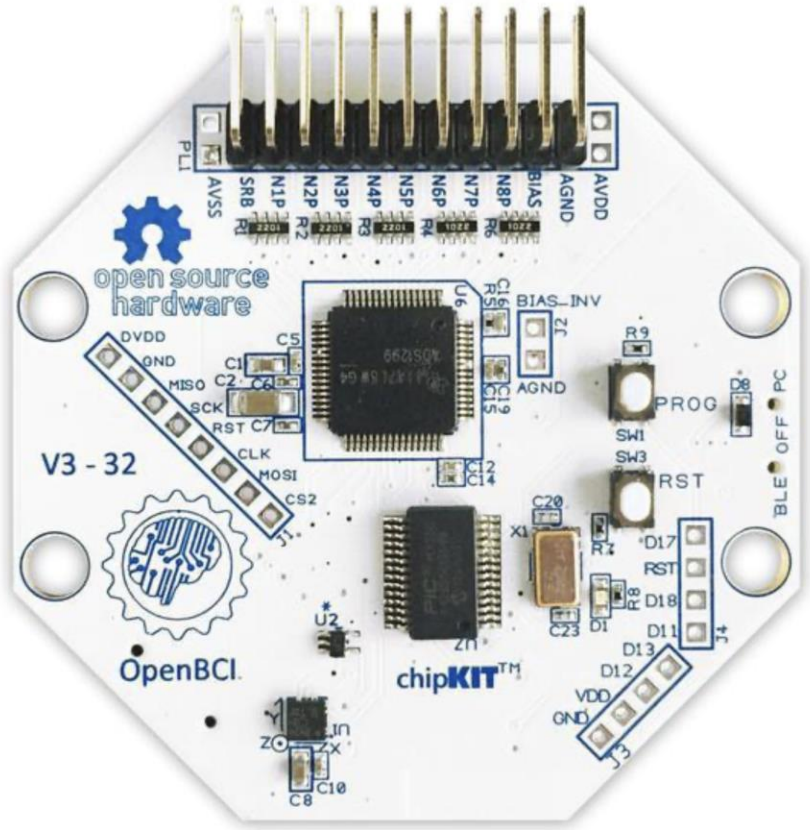


Figure 3. OpenBCI Cyton Board

Final Design

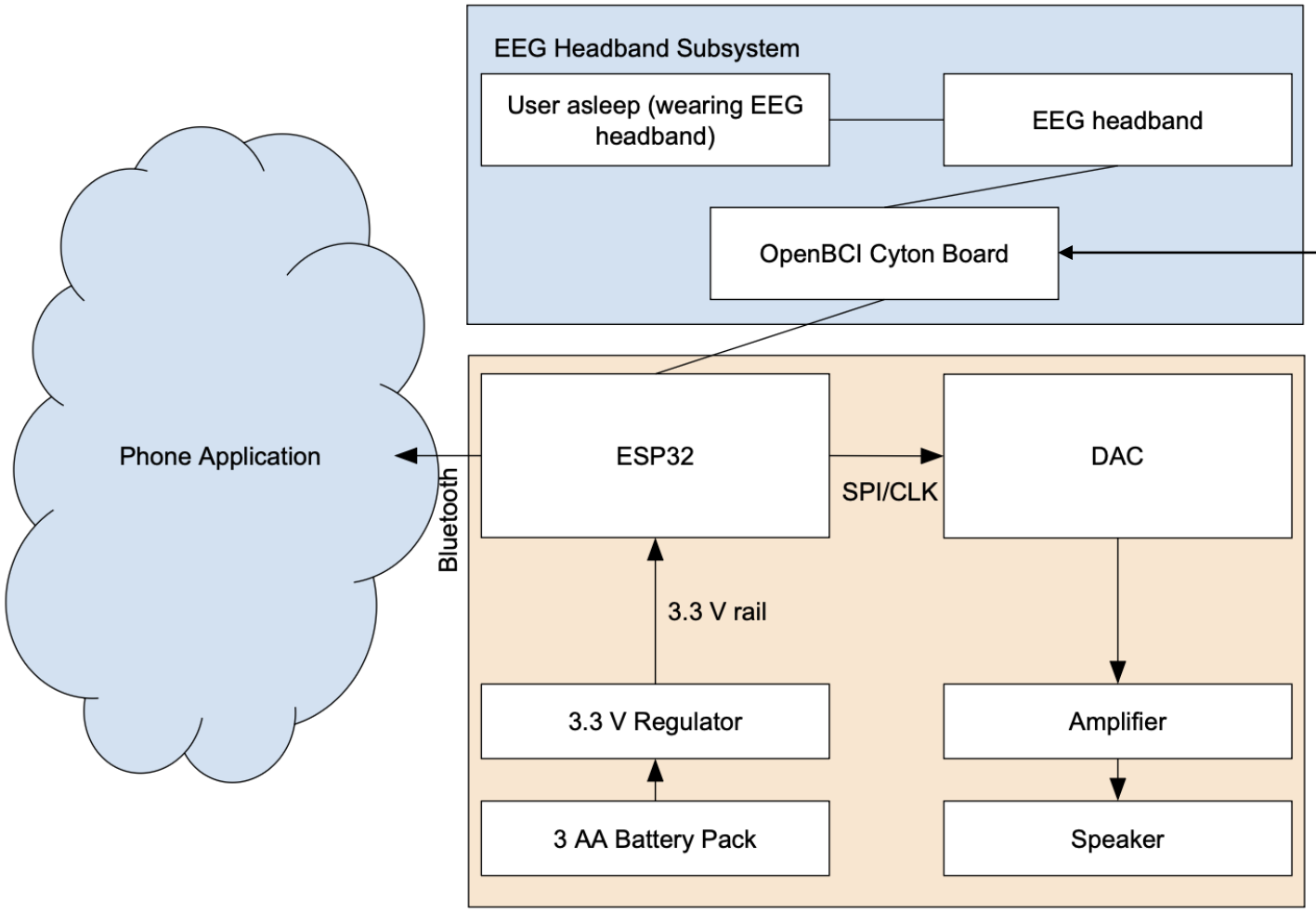


Figure 4. Final Block Diagram

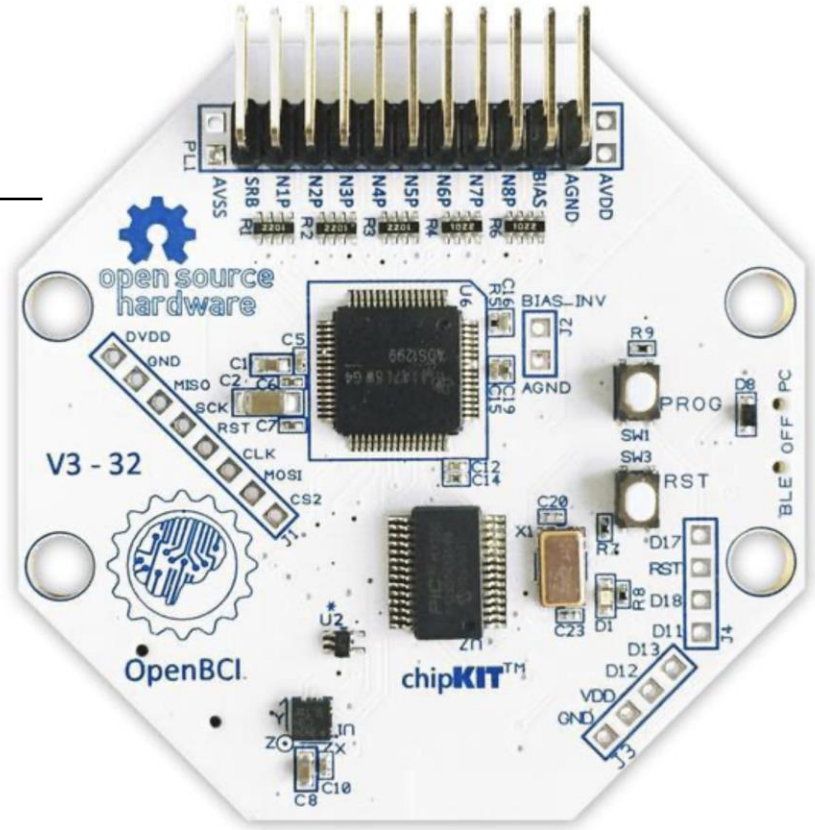


Figure 3. OpenBCI Cyton Board

Project Build & Functionality

Signal Processing Subsystem - Design

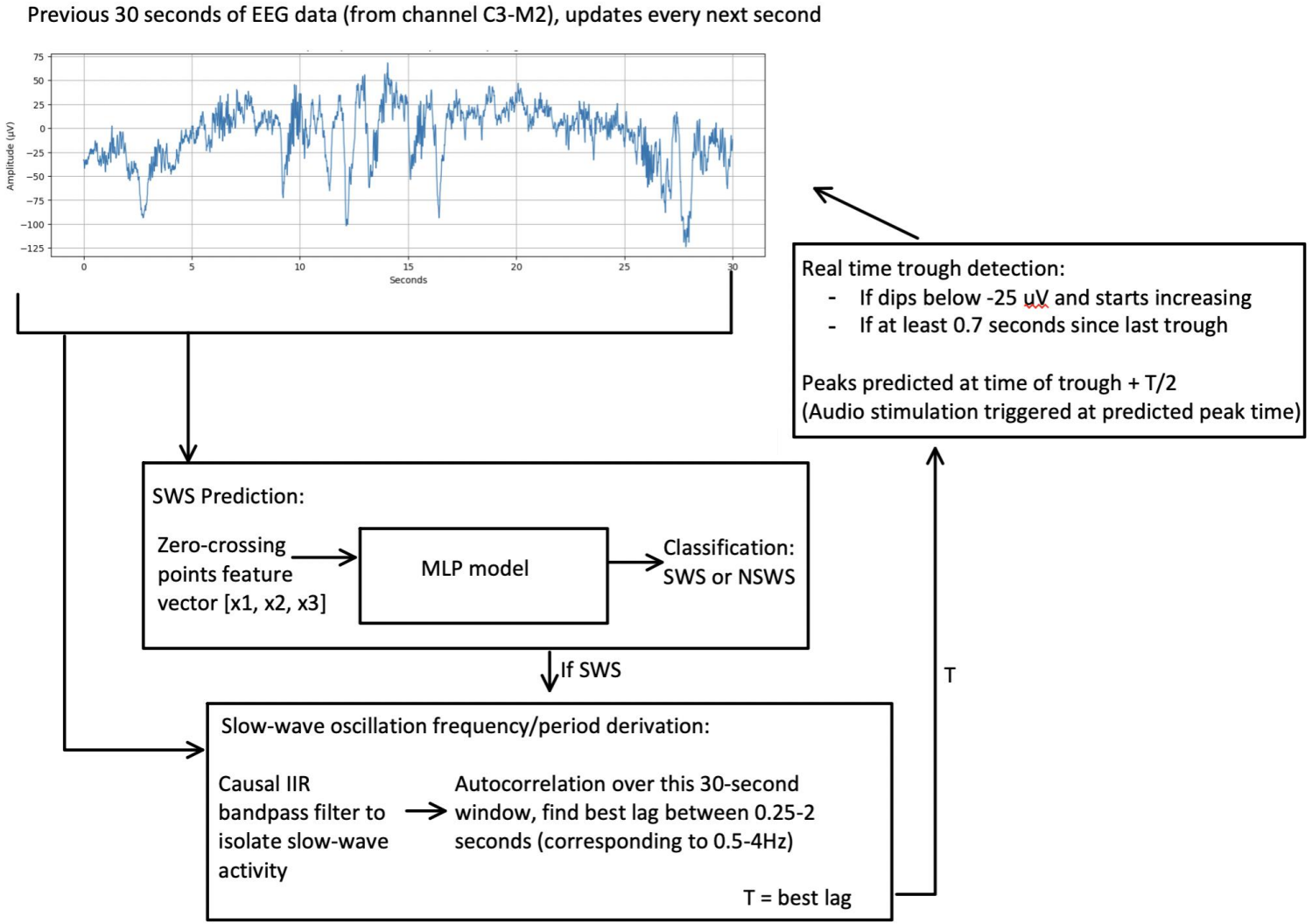


Figure 5. Software Block Diagram

$$\ell_i = e_{i+1} - e_i$$

$$x_1 = \mu_\ell = \frac{1}{I}\sum_{i=1}^{I} \ell_i = \frac{1}{I}\sum_{i=1}^{I}(e_{i+1} - e_i)$$

$$x_2 = \sigma_\ell = \sqrt{\frac{1}{I}\sum_{i=1}^{I}(\ell_i - \mu_\ell)^2}$$

$$x_3 = \sum_{i=1}^{I}(e_{i+1} - e_i)\int_{e_i}^{e_{i+1}} |s(t)|\, dt$$

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

Figure 6. Zero-crossing point-based feature vector

Audio Subsystem - Design

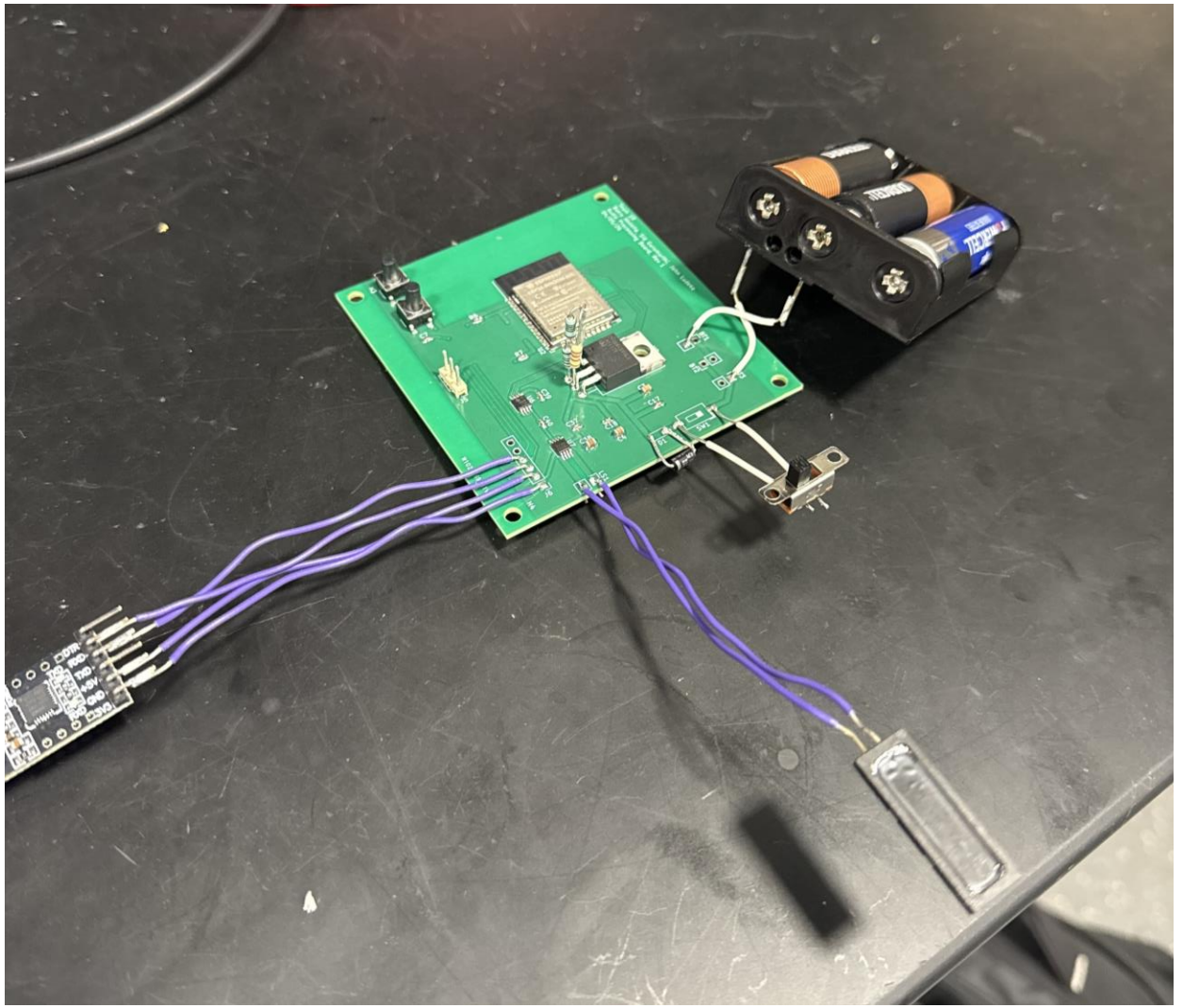


Figure 7. PCB with ESP32 microcontroller & audio subsystem

Testing Functionality

	Predicted NSWS	Predicted SWS
Actual NSWS	7197	339
Actual SWS	95	868

Metric	NSWS	SWS
Precision	0.9870	0.7191
Recall	0.9550	0.9013
F1-Score	0.9707	0.8000
Support	7536	963

Figure 8. Testing Results for MLP Model

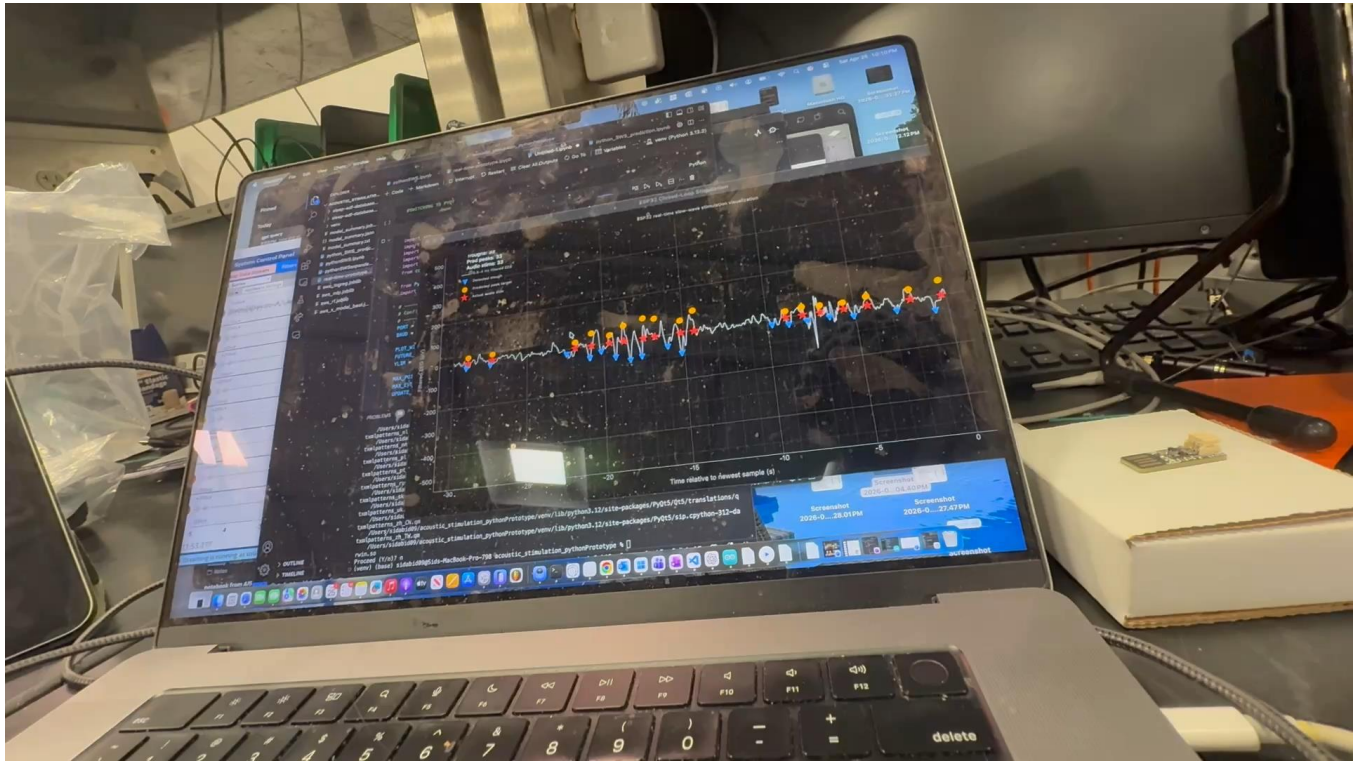


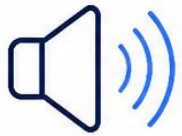
Figure 9. Video of Signal Processing & Audio Functionality

Requirements & Verification

Requirements

Signal Processing

The system must detect slow wave activity in EEG signals with less than 10% signal artifact.

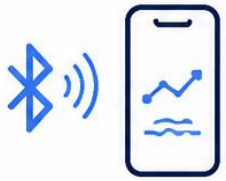


Audio Stimulation

The device shall deliver phase-aligned auditory stimulation within 300ms of slow-wave detection with volume under 50dB.

Power Management

The power system must provide regulated voltage to the PCB for a minimum of 8 hours of continuous operation.



Connectivity

The device shall maintain a stable Bluetooth connection with a mobile application to visualize sleep data without interruption.

Requirements

Signal Processing

Measured 7.06% ADC Saturation over 40-minute recording
(From OpenBCI UltraCortex Mark IV + Cyton Board)

Audio Stimulation

Timestamps recorded – Audio stimulation occurs ~100ms from trough (of slow wave) detection. See Figure 9.

Power Management

Battery capacity: 7500mAh
PCB current: 323mA
Expected battery life: 7500mAh / 323mA = 23.2 hours
(Assumes continuous operation at measured current draw)

Connectivity

ESP32 interfaces with web application through WiFi connection.
Plots data in real time with trough & predicted peak markers.

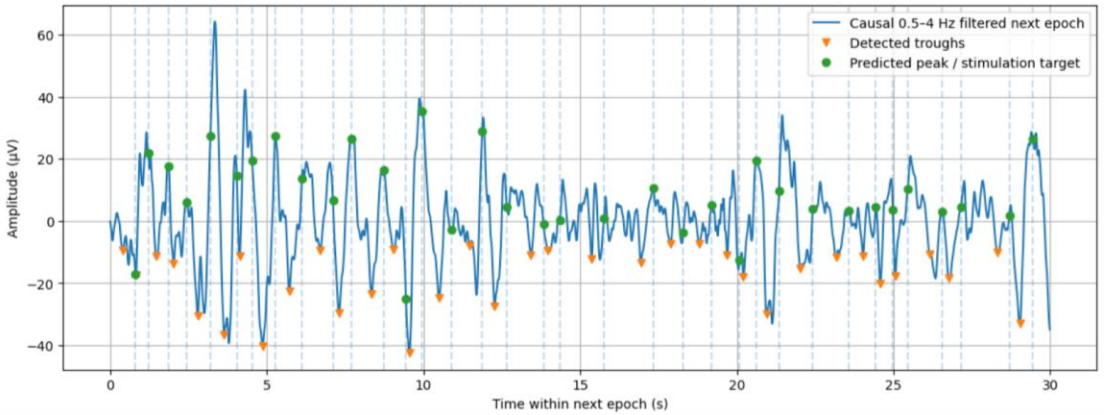
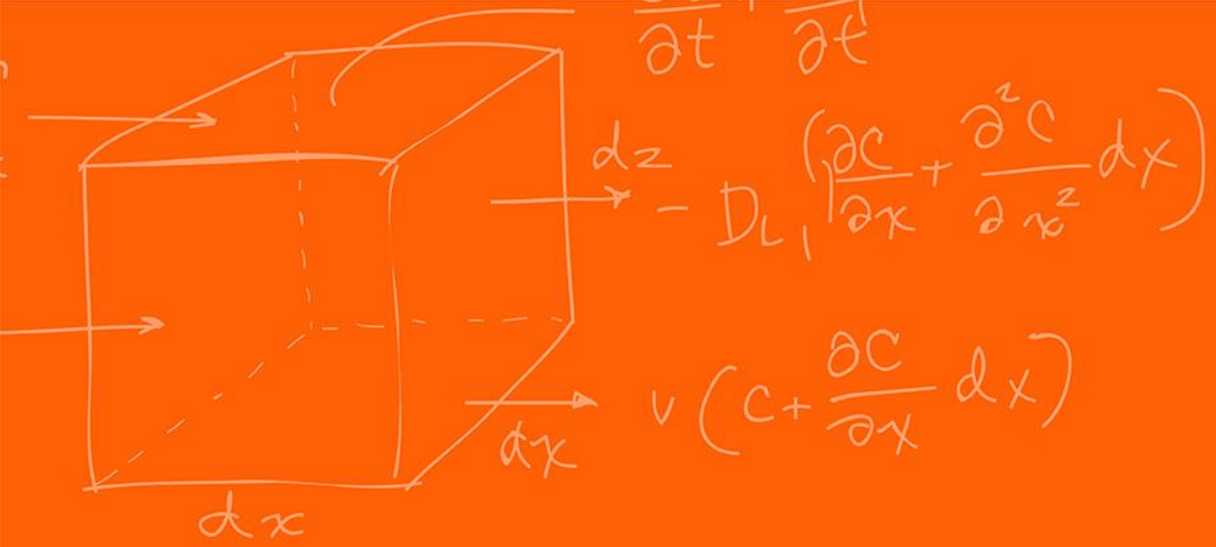
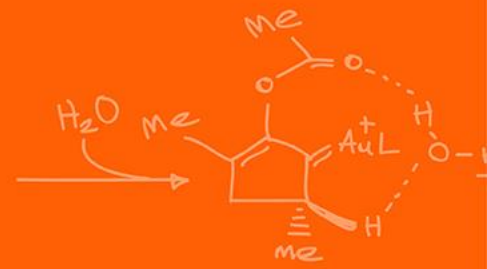
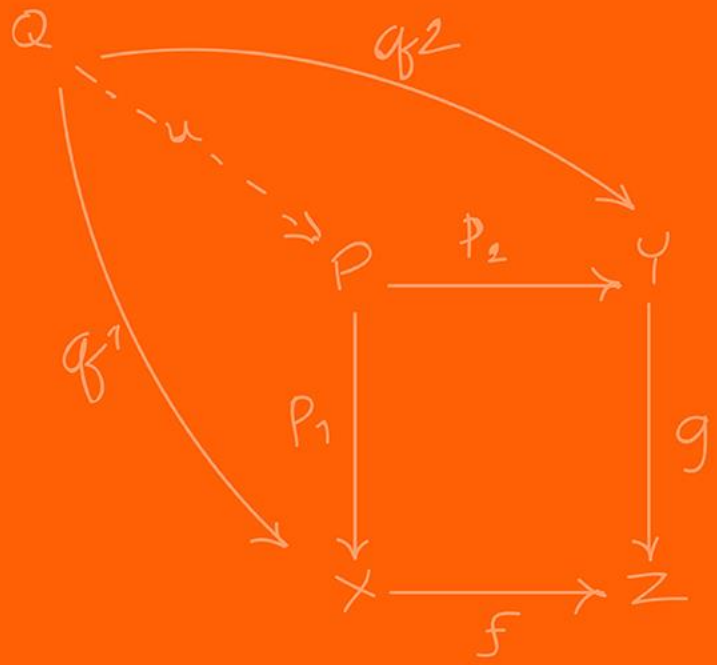


Figure 10. Predicted peaks based on real-time trough detection and slow-wave oscillation frequency for phase-alignment

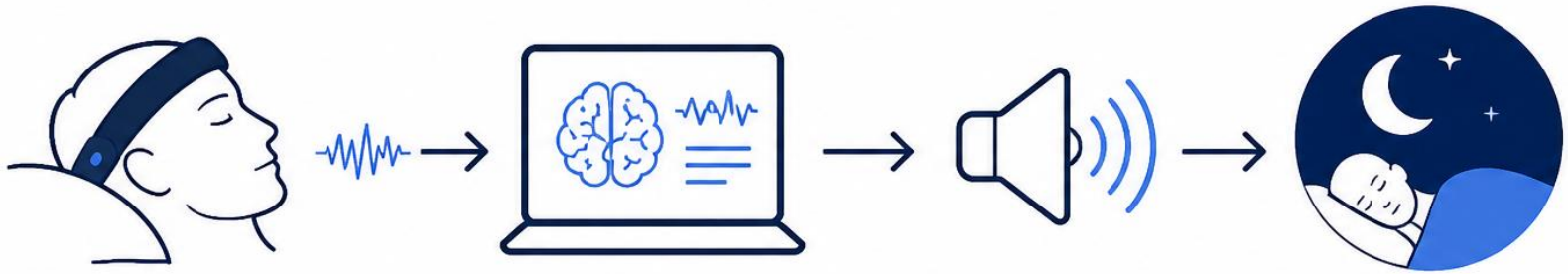




Conclusion



Conclusion



FUTURE WORK

- On-headset processing to reduce latency
- Expand app for long-term sleep trend analytics
- Explore more ML models for better performance

Thank You!

Questions?

Contact Information

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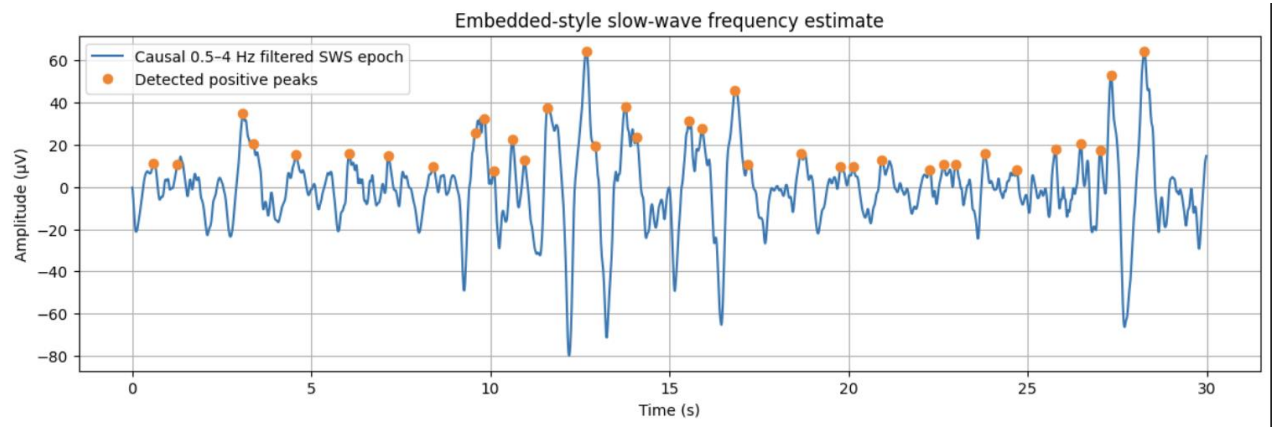
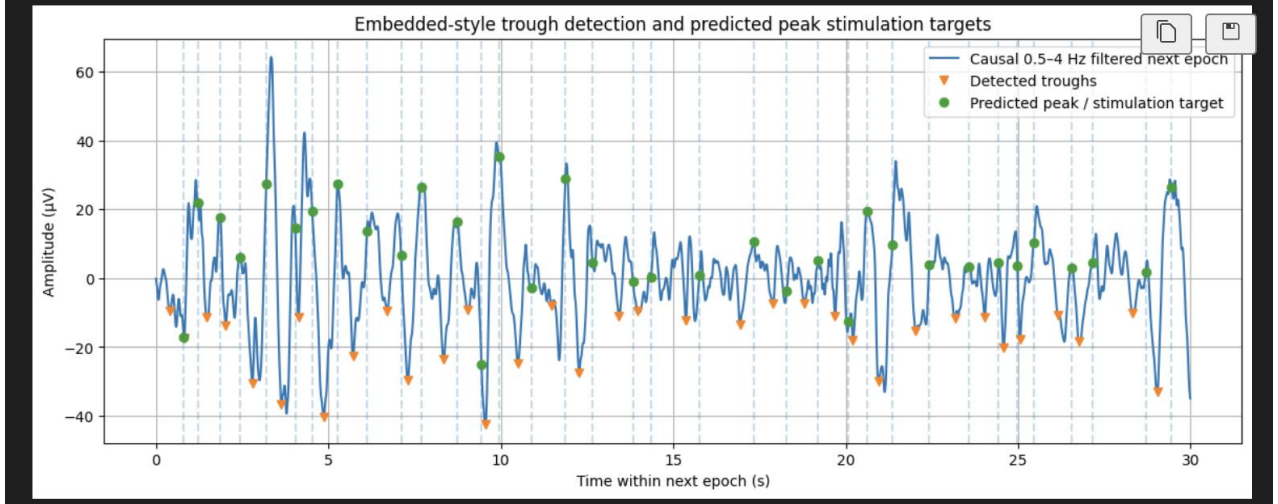
Appendices

Appendix A: SWS Detection Algorithm Visualization and Performance Metrics

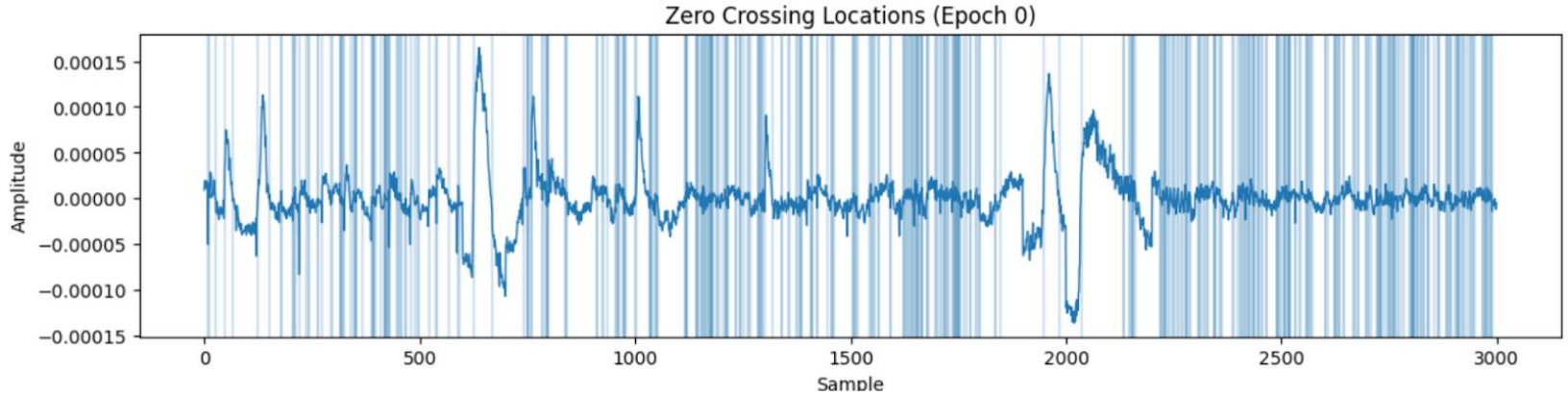


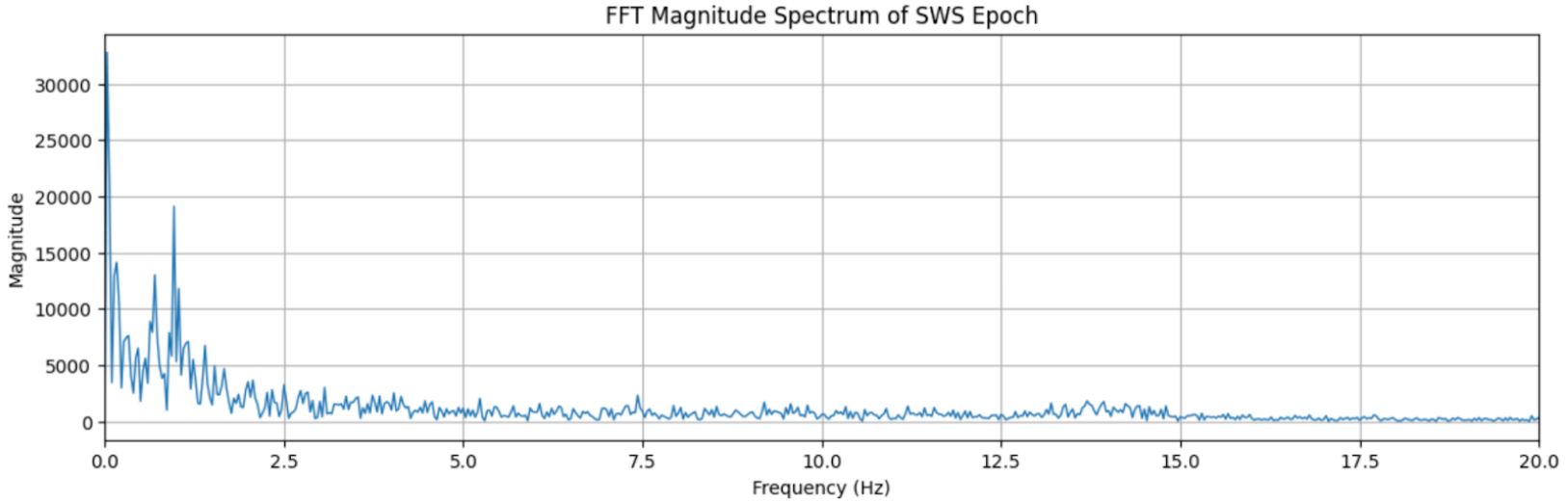

```
B) Next epoch stimulation prediction
Detected troughs: 35
Predicted stimulation peaks: 35
Half-period delay: 0.400 s
Half-period delay in samples: 40 samples
```




```
logreg
Balanced Accuracy: 0.9371227867399514
Confusion Matrix:
[[6737  799]
 [  19  944]]
              precision    recall  f1-score   support

           0     0.9972    0.8940    0.9428      7536
           1     0.5416    0.9803    0.6977       963

    accuracy                         0.9038      8499
   macro avg     0.7694    0.9371    0.8202      8499
weighted avg     0.9456    0.9038    0.9150      8499

==================================================
mlp
Balanced Accuracy: 0.9281829358228995
Confusion Matrix:
[[7197  339]
 [  95  868]]
              precision    recall  f1-score   support

           0     0.9870    0.9550    0.9707      7536
           1     0.7191    0.9013    0.8000       963

    accuracy                         0.9489      8499
   macro avg     0.8531    0.9282    0.8854      8499
weighted avg     0.9566    0.9489    0.9514      8499

==================================================
rf
Balanced Accuracy: 0.9363813818282835
Confusion Matrix:
[[6718  818]
 [  18  945]]
              precision    recall  f1-score   support

           0     0.9973    0.8915    0.9414      7536
           1     0.5360    0.9813    0.6933       963

    accuracy                         0.9016      8499
   macro avg     0.7667    0.9364    0.8174      8499
weighted avg     0.9451    0.9016    0.9133      8499

==================================================
```

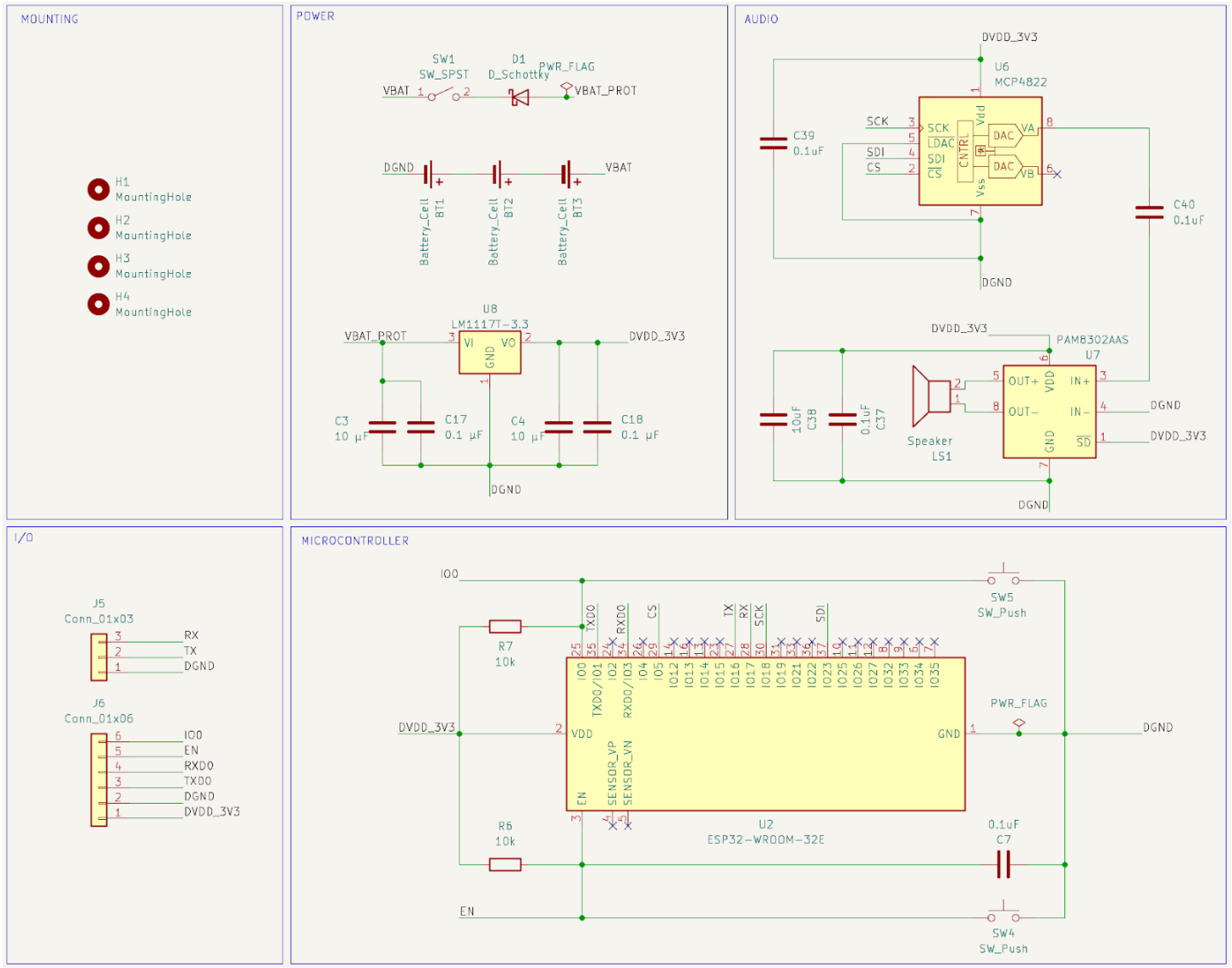
Appendix B: SWS Detection Algorithm Visualization



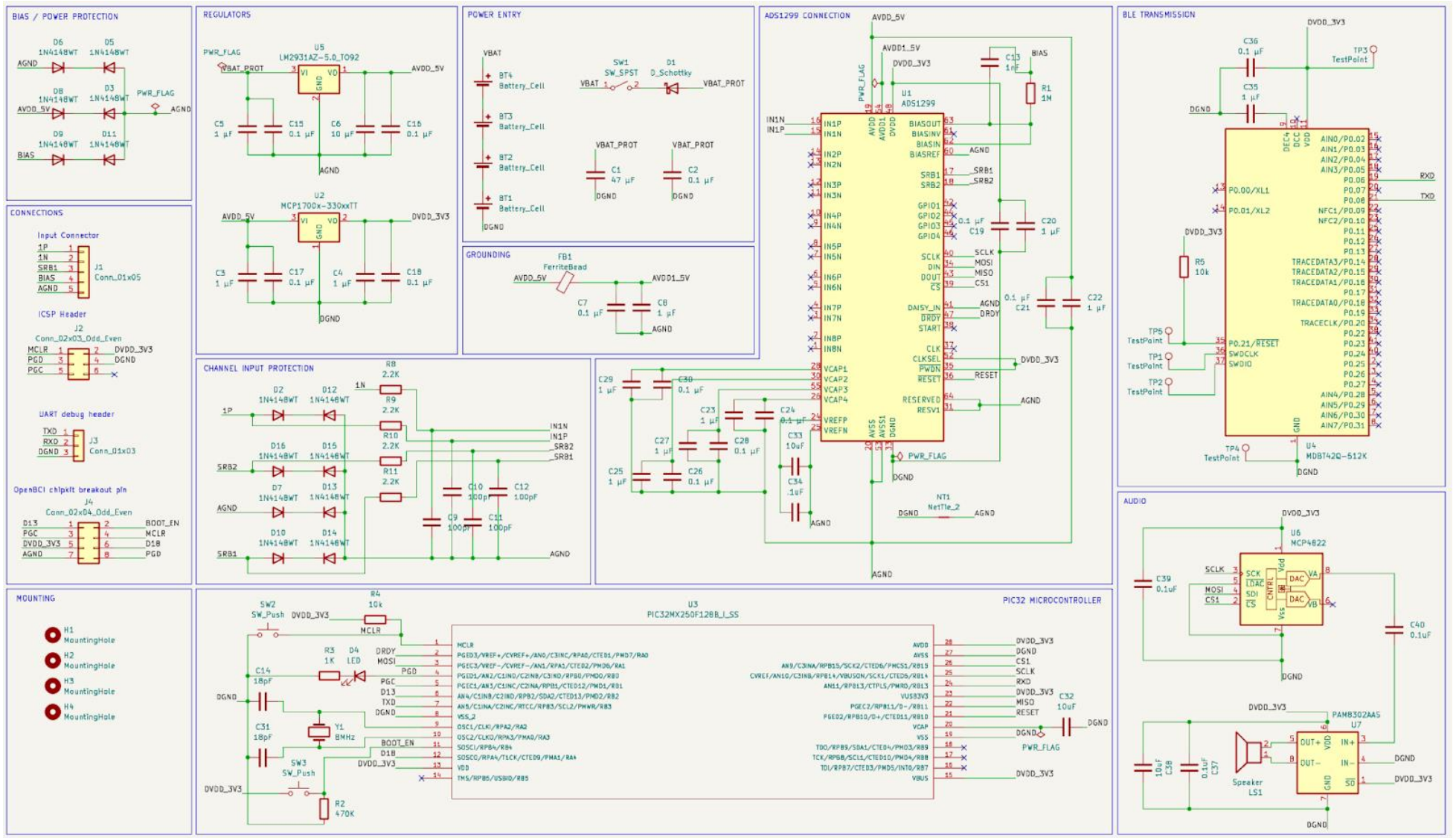



```
A) SWS epoch frequency estimate
Detected positive peaks: 36
Estimated dominant frequency: 1.250 Hz
Estimated period: 0.800 s
```

Appendix C: Final Schematic



Appendix D: Initial Schematic



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