AUTOMATIC SLEEP MONITOR AND TRAIL NAP ALARM

Team 23:
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Industry Sponsor: Dr. Christof Teuscher
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Executive Summary

The purpose of this project is to design and prototype a wearable device which can monitor the wearer's stages of sleep and wake them from a short (10-20 minute) nap after N1 stage sleep, but before REM. This requirement puts the optimal time of awakening during the N2 stage of sleep.

The device fits within a lightweight and unobtrusive headband that passively monitors a person's heart-rate and EEG while worn. It works without user interaction. The device continuously monitors via two electrode probes within the headband on the forehead at locations FP1 and FP2 [1] and a reference probe connected to the earlobe. From this location, both heart rate and EEG signals can be detected using the same probes.

These signals will be passed to a microcontroller within the headband to process and detect when the user is resting, and what stage of sleep they are currently in. It will allow the user to sleep for roughly 15 minutes (starting from N1 stage detection, but including at least 3 minutes of stage N2), but no longer than 30 minutes. The user will then be awoken using a small vibrating motor and sound. We explain the reasoning behind these choices in the following sections.

Background

The design of this device will rely on existing research in biometrics, automated sleep research, and digital signal processing (DSP) libraries for small embedded devices.

Sites FP1 and FP2 were chosen since they are optimal for detecting heart rate, as well as sleep spindles and k-complexes during N2 stage [1].

Research in sleep shows that 20 minute naps are more effective for performance than longer naps, and that sleep inertia occurs after 30 minutes. It also shows that stage 2 has a significant effect on restorative effects, and that at least 3 minutes of stage 2 sleep can be beneficial to performance recovery [2].

NREM sleep is divided into 4 sleep stages, which progress from drowsiness into deep sleep before switching into REM sleep. These stages are accompanied by a series of frequency changes through dominant Alpha (8 - 12 Hz), Beta (12 - 38Hz), Theta (3 - 8Hz), and Delta (0.5 - 3Hz) waves. Stage 1 NREM sleep is best characterized by being easy to wake from and a reduction of Alpha waves in adults. As drowsiness deepens, the slow wave activity grows. At the transition between stages 1 and 2, the phenomena of vertex waves and sleep spindles will occur. At stage 2, eye movement will cease, low frequencies will dominate, and K-complex components will be present. Further stages 3 and 4 will be denoted by the increasing presence of Delta waves.

This project focuses on using EEG signals for sleep stage detection, but there are new developments in using only heart-rate monitoring for this purpose. One such study provides a method for sleep stage detection using just a heart rate signal, with a theoretical recognition rate for N2 stage of 90% [3]. We are not pursuing this method since there are less software resources available. Heart rate nonetheless is still useful for indicating the initial transition from active movement to a resting state.

Product Design Specification

Concept of operations / User stories

Long distance trail runners have to fit short periods of rest in a multiple-day endurance race. Sleep is critical to recovery for runners who compete in races that last for days. In order to get enough sleep and not lose your position in a race, competitors have to time their sleep to the minute. They often have to take short (10-20 minute) naps along the trail. Brief naps have a tendency to leave a person groggy, especially if they are awoken during certain sleep stages, and every person’s sleep cycles are slightly different.

The Trail Nap sleep alarm addresses this issue by monitoring a person’s biometrics and detecting when they are in different stages of sleep in order to awaken the wearer after a duration that leaves them less groggy than if they hadn’t used this device. That duration depends on how quickly the user falls asleep, and how much time they spend on each sleep stage. The device works passively, so the user does not have to take the time to set an alarm, or even engage it when they decide to stop for a nap.

Stakeholders

Dr. Christof Teuscher is a professor at PSU, director of the Teuscher Lab, and an avid trail runner. He is the industry sponsor for this project, and created the initial project proposal we are basing this project on. The team itself is also a stakeholder in this project, as the main researchers and developers for the final prototype.

We specifically designed this system for endurance trail runners. It will be used by our industry sponsor, but we will also make the designs open-source and available to anyone who wishes to build it using our documentation. There are no current plans for commercialization.

Requirements

As quoted from our industry sponsor’s project proposal: “The goal of this project is to build a device that monitors a runner’s sleep and wakes them up after sleep stage N1, before they fall into a REM sleep pattern.” This goal, along with the expectation that a nap will be 15-20 minutes (and no longer than 30 minutes) means that the user will reliably be woken up during stage 2 sleep (N2).

Further requirements include:

- Must detect different sleep stages.
- Must reliably wake person after 3 minutes of stage 2 (N2) sleep, but before 30 minutes of sleep
- Must be small, non-invasive, light, easy to use
- Should have no on-off or other switches
    - We might have a power switch to shut off when not worn
- Should be water-proof
- Must be “ultra-low power”
- Must be battery powered
    - Batteries should last 3 days
    - Should be rechargeable over USB
- May be two devices which connect wirelessly

Specifications

- PocketBeagle with two 3000mAh LiPo batteries will yield ~1200 hours in idle and ~24 hours stressed.
- PocketBeagle integrated LiPo battery regulation
- Target weight limit: ~4 ounces. No more than 0.5 lbs.

Deliverables

- A functional prototype
- Code (on github), nicely documented
- Project proposal
- Weekly Progress Reports to our faculty advisor, as well as to our industry sponsor if they desire.
- Final report
- ECE capstone session poster
- Any other documentation or activities (presentations) the faculty advisor requires
- Electrical CAD: Schematics and board layouts, including output files (Gerbers, PDFs, etc)
- Mechanical CAD: enclosures, mechanisms, including output files (STLs, PDFs, etc)
- Bill of materials and pricing
- Short user manuals documenting how to use the device and software
- Version control, including checked in previous revisions of the design (via git repo)

Initial product designs

Hardware Architecture

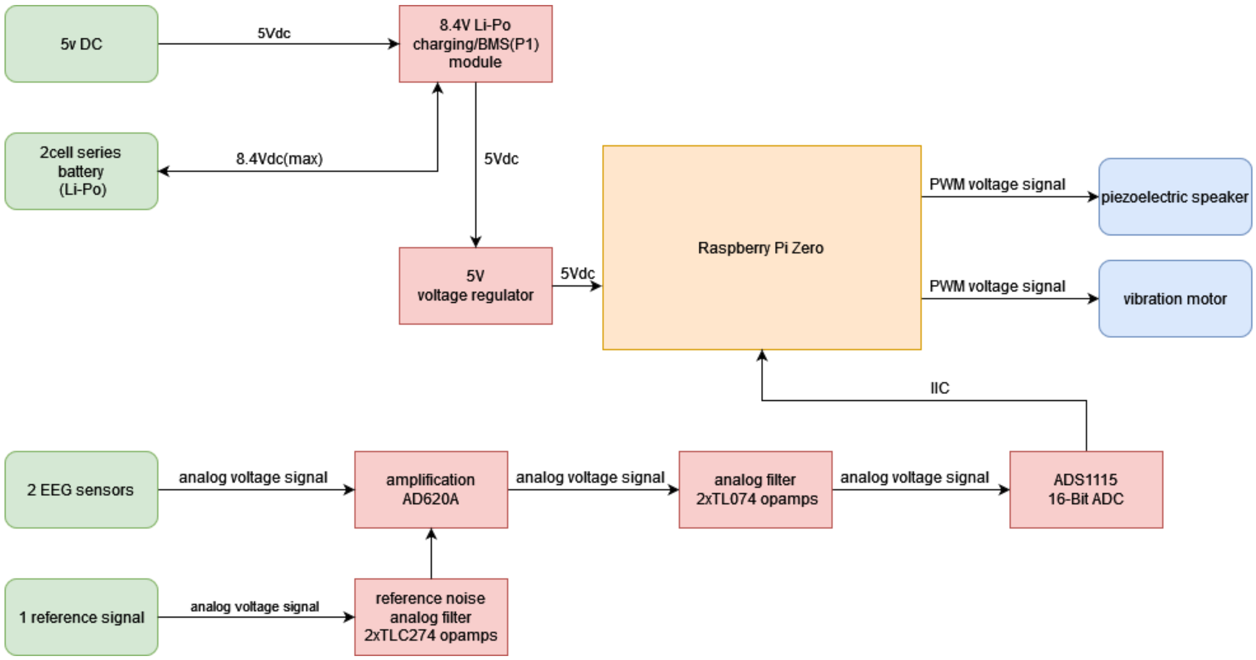

Fig. 1: L1 diagram of Nap Monitor (the Pi-zero has been replaced with a PocketBeagle)

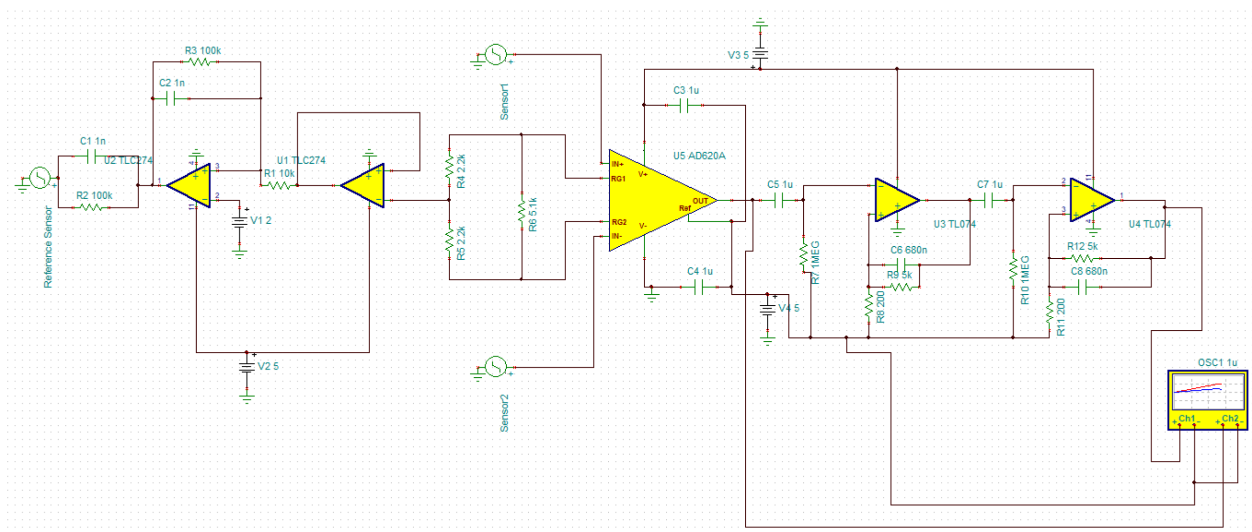

Fig. 2: Circuit design for a dual EEG probe amplification and analog LPF based on the paper, *Portable cost-effective EEG data acquisition system* [4]

The above amplification system allows for common voltages between the two electrodes to be canceled out, thus reducing the noise levels from movement. The PocketBeagle is powered at 5v and can provide power to the amplification circuit. The design of the amplification system includes a method of using a virtual ground for +/- rails.

Microcontroller: ~~Pi Zero~~ PocketBeagle

- Balancing low power and size with processing capacity
- Cheap, accessible
- Easily configurable with peripheral devices

The basic signal chain will go like this: low-voltage noisy signals are amplified, then some rough analog low-pass filtering will occur to pass the analog signal into the ADS1115 ADC. The digital signal will then be passed to the processor via I^2C.

Software Architecture

We intend to use the Python MNE library (https://mne.tools) for developing digital filters and event detection methods. This library, along with the available resources for using Python on a microcontroller, should be enough to allow us to begin software development using the hardware design described in this document.

The signal chain described above will result in a digital time series of EEG data, with a bandwidth of 0.16-47 Hz [4]. From this, the time series is portioned into 20 second segments, called epochs, resulting in a 20 second delay between receiving the first bit of the epoch and any potential output action taken by the processor. Digital filtering is then applied to the epoch using the MNE library to reduce noise from muscle movement, signal drift, EM noise from the device itself (power switching), and heartbeat signals. Further data cleaning might be needed, such as dropping transient artifacts, or discontinuous anomalies.

Once the input epoch is cleaned, we can use impulse convolution methods such as YASA (Yet Another Spindle Algorithm) [5] to detect frequency characteristics, as well as sleep symbols, such as sleep spindles and k-complexes. K-complex detection will play a prominent role in N2 detection. Digital FIR filtering should work for this, since we are less concerned with computation time, and more concerned with retaining an accurate shape of the EEG profile.

The Python environment is a good tool for prototyping digital signal processing methods. Although we might specify a specific method in this proposal, we will have to modify our designs to accommodate the output we will get from our successive hardware prototypes. Python is widely used in the EEG signal processing community and allows us to quickly use existing EEG libraries and datasets to develop digital filter designs and sleep stage detection algorithms.

It is possible we will run into memory and processing constraints using the MNE library directly on the microcontroller. In that case, we will use those tools to pre-process static arrays of impulse responses and wavelets to be convolved in real time and used conditionally on the device processor. This method may not be as robust, but it will be much less computationally expensive.

Sleep studies in the past have required a technician to score EEG data to mark when specific sleep stages occur in the analyzed time series. We plan to use a deep learning algorithm called *TinySleepNet* [6] to score our EEG data for testing and verification (The paper cited for this references *DeepSleepNet*, which has since been updated by the creators to be much smaller and more efficient and renamed *TinySleepNet,* https://github.com/akaraspt/tinysleepnet).

Data Flow:

The digital EEG data stream from the ADC is read by the processor, which creates a 20 second 'epoch'. Digital filtering is then applied to the epoch to reduce noise and get rid of digital artifacts. Heart rate monitoring is used to determine when the user has begun to transition from running to resting. Wavelet convolution and threshold detection are applied to the epoch to detect signs of Stage 2 sleep, such as low frequency brainwaves, k-complexes, and sleep spindles. This process repeats for each epoch, every 20 seconds. Once three minutes of stage 2 sleep has passed, the processor will trigger the alarm system to gently wake the user.

User Interface / experience

The product is used in the following way: the user puts on the headband before the race and wears it throughout. The device monitors the user's heart-rate passively via the two electrodes. At some point, the wearer stops to rest. The headband detects that the user is no longer running and is resting at which point the processor begins to process the electrode input as EEG signals instead of heart rate. As the user lies down and naps, the device detects the initial stages of sleep. Once the device has recorded at least 3 minutes of N2 sleep (with a total duration since first signs of N1 stage no longer than 30 minutes), it awakens the user with an alarm sound and a gentle vibration. The device detects that the user has awoken and shuts off the alarm, returning to heart-rate monitoring as the user returns to running, now refreshed.

Backup plans

- If the device becomes too large for the headband, we plan on separating it into two devices: a control device worn on a clip at the hip and the sensors in the headband. The two devices will communicate wirelessly through bluetooth.
- If we cannot get clean enough EEG signals from our two probes, we will use the same hardware to attempt sleep stage detection using heart rate signals and the method described in the paper *Sleep stage detection using only heart rate* [3].

Verification plans

- We plan to use the Deep Learning system *TinySleepNet* [6] to aid us in sleep scoring for testing purposes. This will verify if our methods are working as intended. This will not be implemented onto the device, but only used externally for testing purposes.

Project Management Plan

Timeline, with milestones

[Gantt chart] included at the end of this document.

Milestones:

- Initial design parts ordered and received
- First DSP prototype working
- First hardware prototype getting usable EEG signals
- Tested 1st DSP prototype with 1st hardware prototype
- Successful real-time sleep stage detection
- 1st wearable headband prototype with successful sleep stage detection
- Fully working prototype that meets all primary “must” requirements

Budget and Resources

The preliminary BoM for our initial prototype is included at the end of this document. The two electrodes and reference voltage clip are not included yet, since we are having difficulty narrowing down the many choices. The price for the combination of these 3 additional components will likely be around $60.
(Initial prototype parts have been ordered, with price under $100 as of 2-18-22)

IP discussion

This project will be licensed under the GNU General Public License. The *TinySleepNet* (https://github.com/akaraspt/tinysleepnet) project is under the Apache 2.0 license for academic purposes.

Team and development process

Team members and areas of focus:

- Nick Porter - Biometrics research, DSP, documentation, communications point person
- Luke Hoskam - research components, prototyping hardware
- Dang Nguyen - hardware, prototyping
- Julia Filipchuk - Software/Firmware programing, Scrum Master
- Michael Weston - Backup plans, Gantt chart, research components and order, organization of drive folder

We plan on using a Trello for sprint objectives, as well as the Scrum method.

BoM for initial Prototype device based on the plan in this proposal

	Item	Diagram Label	Footprint	Vendor	Part Number	Quantity	List Price	Net Price
1	100kΩ resistor	R2,R3				2		**$0.00**
2	10kΩ resistor	R1				1		**$0.00**
3	1MEGΩ resistor	R7,R10				2		**$0.00**
4	1nF capacitor	C1,C2				2		**$0.00**
5	1uF capacitor	C3,C4,C5,C7				4		**$0.00**
6	2.2kΩ resistor	R4,R5				2		**$0.00**
7	200Ω resistor	R11,R8				2		**$0.00**
8	5.1kΩ resistor	R6				1		**$0.00**
9	5kΩ resistor	R9,R12				2		**$0.00**
10	680nF capacitor	C6,C8				2		**$0.00**
11	AD620A Instrumentation Amplifier	U5	8-PDIP	digikey	AD620ANZ	1	$14.91	**$14.91**
12	TL074 Low-Noise FET-Input Operational Amplifier	U3,U4	14-PDIP	digikey	TL074IN	2	$1.28	**$2.56**
13	TLC274 Precision Quad Operatational Amplifiers	U1,U2	14-PDIP	digikey	TLC274IN	2	$2.39	**$4.78**
14	ADS1115 16BIT ADC 4CH PROG GAIN			Adafruit		1	$14.95	**$14.95**
15	Pi Zero W			Pi Supply		1	$10.00	**$10.00**
16	2S 7.4v 8.4v lithium battery charging module USB booster charging board			AliExpress		1	$1.38	**$1.38**
17	903178 3.7 V Lithium Polymer Battery Rechargeable (Secondary) 3Ah			digikey	BL3000F9031781S1PCRV	2	$14.90	**$29.80**
18	Micro USB 5V 2A AC DC Power Adapter			AliExpress		1	$2.78	**$2.78**
							Total:	**$81.16**

References

[1] Malhotra, Raman K. and Alon Y. Avidan. “Chapter 3 – Sleep Stages and Scoring Technique.” (2014).

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[3] Mitsukura Y, Fukunaga K, Yasui M, Mimura M. Sleep stage detection using only heart rate. Health Informatics J. 2020 Mar;26(1):376-387. doi: 10.1177/1460458219827349. Epub 2019 Feb 19. PMID: 30782049.

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[5] Raphael Vallat and Matthew P. Walker (2021). *A universal, open-source, high-performance tool for automated sleep staging*. bioRxiv 2021.05.28.446165; doi: https://doi.org/10.1101/2021.05.28.446165

[6] A. Supratak, H. Dong, C. Wu and Y. Guo, "DeepSleepNet: A Model for Automatic Sleep Stage Scoring Based on Raw Single-Channel EEG," in IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 25, no. 11, pp. 1998-2008, Nov. 2017, doi: 10.1109/TNSRE.2017.2721116.

[7] Sanei, Chambers, Jonathon A., & John Wiley & Sons, publisher. (2021). *EEG signal processing and machine learning* (Second edition.). Wiley.