Aegis: A Biofeedback Adaptive Alarm System Using Vibrotactile Feedback

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1. ABSTRACT

Abstract – **Aegis is a "smart" wireless-wristband alarm system that takes as input not a specific alarm time, as in traditional alarm systems, but rather a time interval specified by a user. The system then automatically chooses the optimal alarm time within that range to minimize sleep inertia in the user after waking. Worn as a wristband, Aegis continuously processes their movement readings to map their sleep stages throughout the night, and remembers the individual user's typical sleep pattern from previous nights, combining these two sources of data to predict where in the sleep cycle the user-set time range will fall. Because sleep inertia is caused by an interruption of deep sleep, Aegis chooses its alarm time to coincide with periods of light sleep, and wakes up the user by vibrating the wristband instead of sounding an alarm, to minimize noise disturbance of roommates, spouses, and/or family members. Preliminary performance evaluation demonstrated the ability of Aegis to track sleep patterns and user satisfaction was confirmed via questionnaires and debriefing**.

Keywords – Biofeedback; Sleep Management; Vibrotactile Feedback; Intelligent Alarm System

I. INTRODUCTION

According to the National Sleep Foundation (NSF), sleep is a physical and mental resting state that is essential for a person's health and wellbeing [1]. Irritability, moodiness, daily sleepiness, and disinhibition are some of the first signs a person experiences from lack of sleep [2]. Furthermore, the degradation in sleep quality is associated with long-term health consequences such as chronic medical conditions such as diabetes, high blood pressure, and heart disease, among others [3].

The ideal location to sleep or nap would be in a soft bed with comfortable sheets, pillows, and a blanket – but in reality people do not always have this luxury. For instance, most students fall asleep on shuttles, on the floor, on couches, on desks, etc. Furthermore, most people do not sleep alone – students and young adults have roommates, children share rooms and bunks with siblings, and couples share beds with their partners. An individual's sleep cycle may be affected by the behavior of others who chronically share the same sleep space.

Human beings are also separated into two chronotypes, reflecting what time of day they are active, computed as "mid sleep on free days" (MSF), the midpoint between sleep onset and sleep end, when sleeping time can be freely chosen [4]. The MSF of an average chronotype is 4.5, meaning their point of mid-sleep is at 4:30PM. Assuming 8 hours of sleep, this person sleeps from about 12:30PM – 8:30AM, without any social obligations in the morning. Chronotypes are ruled by solar, biological, and social clocks, with the former two being considerably stronger factors than the latter one – therefore, a person's chronotype cannot be changed merely by "getting used" to certain time schedules [5]. These are attributed to the intricate and complex behavior of the individual's circadian rhythm, thus providing further proof that it is not enough to simply abide by the "8 hours a night rule." Every person has individual needs which stem from not just lifestyle and preference, but also from biological effects.

"Larks" naturally go to bed and wake up between within two hours earlier than the norm, and are most alert when the sun is up; "owls" go to bed and wake up within 2 hours later than the norm, and are most alert at night. Chronotypes affect sleep timing, but not vice-versa – a lark attains the most restful sleep at the aforementioned hours, but if a sudden change forces a lark to go to bed 4 hours later than usual, he / she would naturally still wake up early. This is yet another reason why it is insufficient to schedule sleep based on the standard "get 8 hours a night" rule, because it disregards the inner biological activity of individuals. A product like Aegis does not make its decisions based on how much sleep a user should get, but rather, how to time sleep so that a user gets the most out of it. Furthermore, age and gender play a role in the biological clock that governs individual chronotypes [6].

Researchers have identified the various phases of sleep [7]. We classify sleep into REM (Rapid Eye Movement) and non-REM phases. Non-Rem phase includes N1 (conscious awareness of the surroundings slowly disappears within 20 minutes after sleep onset), N2 (increased appearance of sleep spindles and complete withdrawal from external awareness), and N3 and N4 (commonly summarized as slow wave sleep (SWS) or deep sleep) [8]. Together, N1 and N2 are known as light sleep, characterized by the lowest arousal threshold (level of stimulation needed to wake up an individual while in a particular stage) of all sleep stages. Adults spend at least 50% of total sleep time in light sleep.

On the other hand, REM phase is identified by rapid eye movement and intense atony of skeletal muscles. Abruptly waking someone during the REM phase can cause sleep paralysis, which is defined as the sudden experience of an inability to move combined with terrifying visions to which one is unable to react due to this paralysis. This phenomenon occurs due to the particular biological attributes seen in REM sleep: complete muscle paralysis, dreaming, and irregular breathing and heart rate. A sudden snap back to consciousness often results in the brain's recognition of these sensations as panic, suffocation, and visual hallucinations. Immediately after REM, however, a period of light sleep returns, and the body has completed one entire sleep cycle. Therefore, waking immediately after REM, immediately after the completion of a cycle, limits sleep inertia most effectively. An individual moves through several sleep cycles of approximately 90 minutes in which NREM and REM alternate [9].

Aegis functions as an alarm that users can physically wear on their wrist, that doesn't require Internet connection, and, most importantly, features vibrotactile actuation which can be utilized anywhere and without disturbing others. During its calibration mode, the Aegis system records data across several nights of "typical sleep" – whether a typical night includes screaming babies or a spouse's return from a late shift – and use averages to represent the normal sleeping pattern for that individual. Because Aegis system is equipped with a vibrotactile actuator, it will wake only the person who intends to wake up, and not their partner. The vibration intensity may be manually set higher or lower, for example, if the client knows that their roommate is a heavy sleeper, or if the client sleeps in the same room with an elderly (the elderly spend less time in deep sleep and are more easily awakened by environmental disturbances).

The remainder of the paper is organized as follows: section 2 describes related work and highlights the scope of this paper. In section 3, we present the software architecture of the proposed system and elaborate various components of the system. Section 4 presents implementation details and hardware used in the prototype. Section 5 describes the performance evaluation and user feedback. Finally, in section 6 we summarize the paper findings and provide perspectives for potential future work.

II. RELATED WORK

There exist several techniques to track sleeping cycles and measure the quality of sleep. The most common and simple one is using actimeter/actigraph [9-10], a watch shaped accelerometer worn on the wrist to measure the user activity during sleep. There are strong correlation between wrist activity and detection of sleep/awake status [11]. Researchers in [12] reported more than 90% agreement between actimeter and PSG. Although the total sleep time can be measured using an actimeter, it cannot give a trustworthy measurement for the sleep quality, rather it measures the sleep efficiency that is defined based on parameters such as sleep time or total time in bed [13].

Many features of modern sleep-tracking alarms and monitors, such as the tracking of the sleep cycle and sleep optimization, already exist in today's market [14]. However, most of these systems rely on motion sensors through indirect contact, rather than directly reading sleep frequencies with EEG signals, and none have as comprehensive and intelligent a system for optimizing sleep as proposed, considering the hours last slept, the hours usually slept, the sleeping environment, and the person's age.

While dealing with monitoring the sleep quality of a person, getting the correct data from the monitoring device is of primary importance. Researches have been done to find a way to improve the quality of biomedical signals that devices like EEG and ECG sense. One research carried out in State Key Laboratory of ASIC and System Fudan University shows that one of the problems that results in getting inaccurate signals from the EEG is because of differential DC offset voltage that rises due to interface between electrode and skin which decreases common-mode rejection ratio (CMRR) [15]. This research also recognizes the extremely week amplitude of the signal we get from the EEG as a major drawback as it makes it highly prone to noise. AC coupled instrumentation amplifier and Programmable gain amplifier are the two solutions suggested for improving the structure of the Readout Front-End (RFE) used for sensing the biomedical signals.

Another study from School of Engineering and Advanced Technology Massey University suggests positioning the sensing device close to the person to get the most accurate data [16]. This research focuses mainly on helping care takers monitor the activities of elderly or disabled people by placing the sensing devices on the appliances that are most frequently used by the person under monitor which includes the bed. It suggests using an intelligent bed sensing system for monitoring whether the person is on the bed or not, whether the person is sleeping or not and for gathering information regarding the sleep quality. Weight sensing sensors will be placed under each leg of the bed. Each of these sensors gives a horizontal line when there is nothing on the bed or some sort of reading when the bed is occupied. Comparing the responses of the four sensors is used to monitor the quality of sleep the person is getting. If a person is having a good sleep, the frequency graph of each sensor will be similar; otherwise the unevenness of the graph suggests a disruption in the normal sleep cycle.

A similar study suggests the use of an economical system consisting of multimodality sensors with machine learning approaches for human sleep–wake detection and sleep-quality measurements [17]. This study introduce either an infrared night-vision video webcam or a Passive Infra-Red (PIR) sensor for data capturing regarding motion of the user which will show whether the person is sleeping or not and a wearable watch with a sensor belt to capture the users heart rate which varies according to the state of sleepiness the person is in. A PIR sensor detection works when a heat emitting source crosses two adjacent sector boundaries or crosses the same boundary twice within a specified sensing time (the PIR is modified to have a 2 seconds resolution time in this study). Motion occurs frequently and is relatively irregular while a person is awake (compared to the sleep condition). The motion to time ratio is used to determine whether the person is sleeping or awake. Using the signal from the wearable watch and analyzing the ration of low frequency to high frequency, this device will determine the transition from wakefulness to Non-Rapid Eye Movement (NREM) to Rapid Eye Movement (REM);

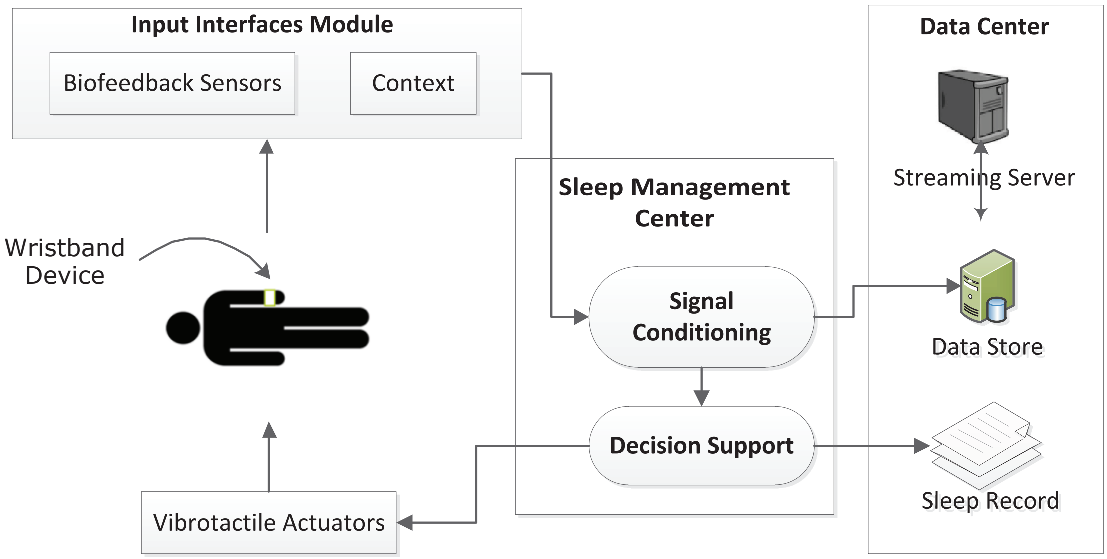

Figure 1: Software architecture for the Aegis system

the ration of low frequency to high frequency will decrease and increase respectively. This device uses the combination of both signals to decide the state of sleepiness of the person.

Sony has recently submitted a patent for an alarm pillow to US Patent and Trademarking Office [18]. This pillow has electrodes on the surface that are arranged to come in contact with the head and act as sensors, a brain wave signalacquisition section to read and acquire a brain wave of the user through the electrodes, an analysis section to interpret the signals to determine when the user goes in to REM and comes out of it and a control section which controls when the buzzer or a flash light embedded in the pillow will go off. This pillow is designed so that the alarm (buzzer or flashlight, bed shaker, etc.) goes off as soon as the person gets out of the deep sleep.

Aegis is different from this pillow alarm because we are going to design it so that the alarm goes off with a certain range of time from the time that the user sets the alarm. It doesn't wake the user up only after REM like in the case of the pillow alarm. The REM stage of the user might be short or long depending on different situations, thus the pillow alarm might wake up the user too early or too late than the set time. Our product, on the other hand, approximates the alarm time so that the user wakes up while he is on stage two of the sleep cycle but still within a good range of the alarm time that was set by the user.

III. AEGIS SYSTEM DESIGN

Figure 1 shows an overview of the proposed Aegis system. The user wears wristband device that measures user movements along with contextual information and sends the data to the sleep management center via Zigbee wireless communication technology. The sleep management center derives sleeping behaviour and sets a vibrotactile alarm in a way to minimize sleeping inertia. Furthermore, the collected data is stored and streamed to a third party user using the Data Center module.

A. Input Interfaces Module

The Input Interfaces Module reads biofeedback data about the user, along with the context, and passes the collected data to the Sleep Management Center. The components of the software architecture are described briefly here:

- *Biofeedback Sensors:* This component acquires physiological and/or psychological data about the sleeping person. In particular, hand movement is tracked using an accelerometer as a completely non-moving hand indicates deep/shallow sleep so that the alarm can be set accordingly. Other biofeedback sensors can be added to the Input Interfaces Module to achieve a higher accuracy of detecting sleeping phases.
- *Context:* The context component collects information related to the place, time, and circumstances around the sleeping user. Examples of contextual information include, but not limited to, location, time, ambient noise, and light conditions.

B. Sleep Management Center

The Sleeping Management Center is the heart of the Aegis system. It includes a signal processing module and a decision support module that implements the alarm according to the sleeping patterns of the user.

- *Signal Conditioning and Processing:* This component minimizes (and possibly eliminates) signal artifacts such as disturbances and information damage that severely deteriorate the accelerometer readings and thus the motion estimation.
- *Decision Support:* The Decision Support component includes a knowledge-based system for sleeping patterns that is used to identify sleeping cycles for the user and compile biofeedback and context information to identify shallow sleep phases and set the vibrotactile alarm accordingly.

C. Data Center

The Data Center is a repository to store data related to the Aegis system and a streaming server to share the collected data with a third party (such as a family member or a therapist) by providing online and offline streaming.

- *Streaming Server:* The streaming server is a facility that is capable of transmitting data stored in the Data Center to a third party via a Web Service Architecture or a cloud computing architecture (a decision made at the implementation level). The streaming server implements a communication protocol that standardizes access to Aegis data and resources.

- *Data Store:* The Data Store component is a database that saves performance about the sleeping behavior of the user as well as the history of sleeping performance. For instance, the Data Store includes the time-stamped movement information and a snapshot of the context at every phase of the sleeping cycle. The database will table the following information for each tested user:
  - The time at which the user set their alarm
  - The time Aegis chose to wake them up
  - Duration of sleep
  - Location of sleep
  - Ages of cohabitants
  - Age of user
  - Chronotype

- *Sleep Record:* The Sleeping Record stores the user profile, Aegis configuration and settings, as well as performance data (the movement data as well as the identification of sleeping phases). Examples of user's profile information include user age and gender, user preferences as for sleeping context (ambient noise, light condition, room temperature, etc.).

D. Vibrotactile Actuators

The Vibrotactile Actuators are small motors that vibrate at various frequencies and intensities to convey tactile sensation feedback. The Vibrotactile Actuators are controlled by a microprocessor that receives commands from the Decision Support component and generates actuation signals that control the vibrotactile motors. The actuation circuit is composed of four vibrotactile motors that are arranged around the wrist and can be actuated separately or in sequence (for instance clockwise or anticlockwise).

E. Optimal Alarm Time Determination

The algorithm used for adaptive alarm time determination is defined as follows:

I. If user-set window begins within 60 minutes after bedtime, optimal time = anytime within user-set window,

II. If it begins between 60 – 115 minutes after bedtime, optimal time = a few minutes after SWS-FWS,

III. If it begins between 115 minutes – second third after bedtime, multiple times can be determined in order of priority:
   a) Optimal time = a few minutes after N2-N1
   b) Priority 2 = a few minutes after SWS-FWS
   c) Choosing between the two depends on calibration history – if the alarm window begins before rise01, Aegis will choose the latter, and if it begins after rise01, it will choose the former.

IV. If it begins beyond the second third, optimal time is set to a few minutes after N2-N1.

IV. SYSTEM IMPLEMENTATION

The implementation architecture, as shown in Figure 2, is composed of an ADXL-335 accelerometer to measure user's hand movements, an Arduino Pro Mini microprocessor to read acceleration data, implement the sleeping management logic, activate the vibrotactile motors, and communicate sleep-related data with a third party device using the X-Bee Transceiver, and a 3.7V Lithium battery.

The wristband device is composed of the following components:

- 1 ADXL-335 accelerometer
- 1 Arduino Mini Pro
- 3.3 – 5 V voltage regulator
- 1 XBee pair
- 1 vibrotactile actuator
- 1 DeadOn DS3235 RTC {Real Time Clock}
- 1 power cell & 1 battery

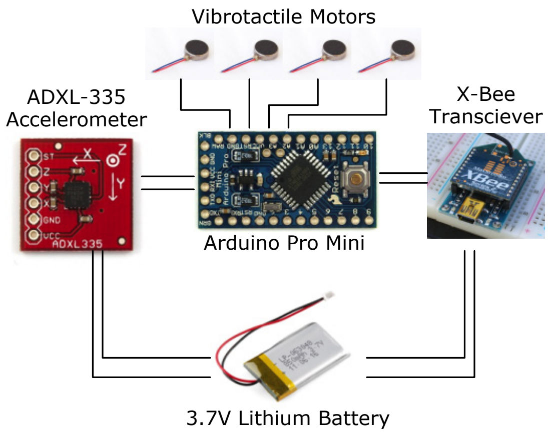

Figure 2: Implementation architecture for Aegis system

Supplementary components that are also used for the Aegis system include:

- 1 battery charger
- The other XBee, on a mini-USB compatible breakout board
- 1 mini USB cable
- 1 FTDI chip

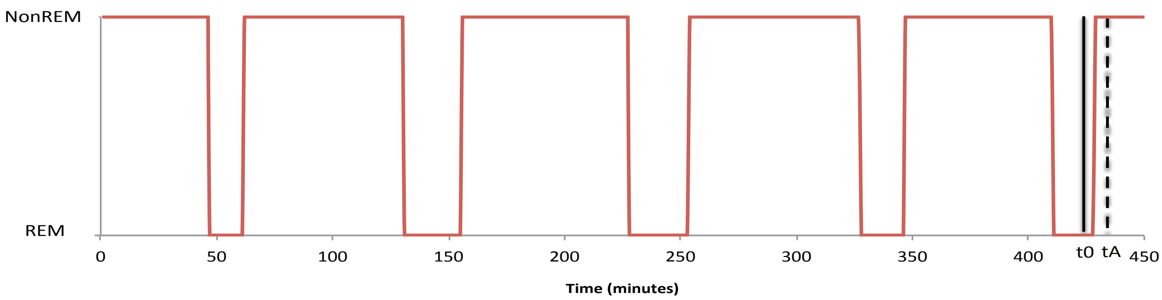

Figure 3: Shifting alarm time forward (from t_0 to t_A) to avoid waking the user during REM phase.

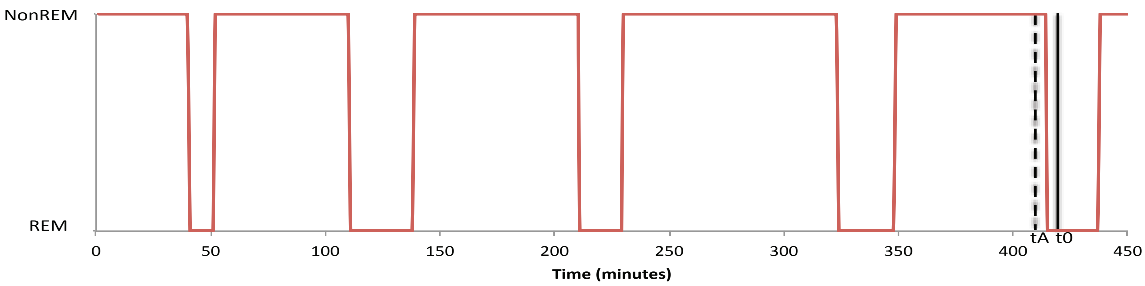

Figure 4: Shifting alarm time backward (from t_0 to t_A) to avoid waking the user during REM phase.

As for the software development environment as well as the real-time streaming, the following components were used:

- Processing
- Bloom
- SensorMonkey Namespace & Public Key
- HTML editor
- Python
- Javascript files: processing-1.4.1.js and socket.io

V. PERFORMANCE EVALUATION

The objective of this study is to explore the usability and effectiveness of the Aegis system as a tool to sleep management. Ten adult subjects (5 male and 5 female) participated in the experiment; their ages ranged from 17 to 23 years. All participants have experienced (occasional) sleep inertia and thus expressed interest in the Aegis system.

Figure 3 and Figure 4 show examples of sleeping patterns for two different users. In both cases, the Aegis system was able to detect REM and non-REM phases and derived personalized patterns, after 1 week of training cycles. For example, in Figure 3, the alarm time has been moved forward (from t0 to tA) to avoid waking the user during the REM phase whereas in Figure 4 the Aegis system has shifted the alarm time backward just before the user goes into REM sleeping phase.

Furthermore, a usability study has been conducted to evaluate the Aegis system performance and user's feedback. The participants were given a prototype of Aegis system and used it for two weeks: the first week data was used to train the system according to the user's sleeping pattern whereas the second week was used to minimize sleeping inertia.

As part of the usability evaluation, questionnaires were given to the participants by the end of the two weeks where the most important four questions statistics are shown in Table 1. The four questions were: Q1: Did the system help reducing sleeping inertia? Q2: Would you buy system at affordable price? Q3: Do you think the device has compromised your privacy? And Q4: Did you feel uncomfortable wearing the device?

As shown in Table 1, the results are promising. All subjects (100%) confirmed that the Aegis system has clearly decreased sleeping inertia they used to experience on the second week of the experiment. Eighty percent (80%) of the subjects have expressed interest in purchasing the system for affordable price. Furthermore, only one subject (10%) of the participants felt that the Aegis system compromises their privacy and they felt been watched while sleeping. Finally, 30% of the subjects expressed that the device is not quite comfortable to wear. This is understandable since we used prototypes in this study. A more compact and professional finishing of the system may provide a higher level of comfort to the subjects and thus better usability.

VI. CONCLUSION

This paper presented Aegis system – a smart wireless-wristband arm system for sleep management and reducing sleep inertia. The system was demonstrated to track the user's sleeping pattern in terms of REM and non-REM phases. Furthermore, usability testing has shown clear interest from the participants to use the system while few expressed concerns about privacy and comfort related to the implemented prototype.

However, as the prototype evolves, further improvements can be made to the system. The hardware could be optimized in terms of size (for example, the circuit should move to a

Seeeduino microprocessor [19] for even more compact assembly), and sensory data should be saved in its internal memory (EEProm). A mobile device application may also be developed to provide a convenient interface to the system (as well as the design of the graphical user interface). Finally, further usability studies could be performed (over longer time intervals) to further analyze the system and derive a more robust and accurate sleeping patterns per subject.

Table 1: Subjects responses to four key questions in the questionnaire.

	Response	5 (Female)	5 (Male)	% Total
Q1	Yes	5	5	100%
	No	0	0	0%
	Not Sure	0	0	0%
Q2	Yes	4	4	80%
	No	1	0	10%
	Not Sure	0	1	10%
Q3	Yes	1	0	10%
	No	3	4	70%
	Not Sure	1	1	20%
Q4	Yes	2	1	30%
	No	3	4	70%
	Not Sure	0	0	0%

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