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Central Sleep Apnea Detection and Stimulation

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Abstract— **This paper proposes a system to detect and intervene in instances of central sleep apnea. The system is composed of a detection module and a stimulation module, which provides sensory stimulation to the patient when an apnea event has occurred. The system is currently in prototype and has not yet undergone patient trials.**

I. Introduction

ELECTRICAL sensory stimulation has been shown to be effective in treatment of various brain pathologies such as stroke and dementia [1], [2]. We have recently applied similar principles of sensory electrical stimulation as a means to push the brain out of its apnea state. This approach is not new to the research of sleep apnea [3], but unlike obstructive sleep apnea studies, muscle stimulation is not a desired outcome. The concept is to provide external electrical stimulation during an apnea event to the arch of the foot, a region of high sensitivity. The desired outcome of this stimulation is a resumption of normal breathing without waking the patient. Stimulus pulses become successively stronger if initially unsuccessful, eventually resulting in brief patient arousal, who then exits the apnea event [4]. The approach is currently in the prototype stage and requires further research and testing to be conclusive. Although sensory stimulation related to central sleep apnea is relatively untouched, several groups have published and even patented techniques to stimulate the phrenic nerve to combat apnea events [5] [6] [7]. The works of Ponikowski et al. show that stimulation of the phrenic nerve does indeed restore normal breathing to patients with Central Sleep Apnea (CSA). These works hint that stimulation can provide successful relief from apnea events. Unfortunately, the phrenic nerve stimulation requires invasive placement of electrodes, something that may not be welcomed by the average patient. The CPAP machine is currently the de facto treatment that is used to treat apnea patients. These devices continuously force air into a patient's lungs in order to keep them oxygenated, regardless of if their respiratory muscles are actually functioning [8]. The mask that the patient is required to wear with this technique, coupled with the noise of the pumps, may impede the ability of the patient to fall asleep. In addition, CPAP is not effective for apnea cases where high CO_2 is the primary driving factor of an apnea event [4]. The goal of the design proposed in this paper is to create an alternate method that will treat apnea events without being evasive or discomforting. This is accomplished through the use of a belt based transducer, and a leg mounted stimulator, enabling patients to remove the need to wear bulky masks associated with traditional treatments. Intervention in apnea events is achieved through application of stimulus pulses to the patient.

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II. System Overview

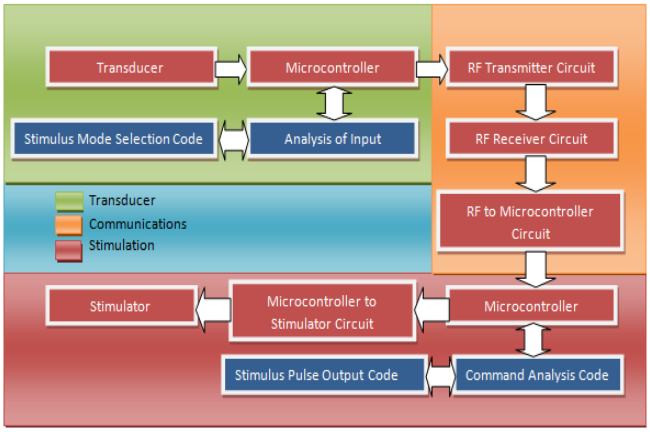

Fig. 1. Main system overview. The system is composed of three main subsystems, the transducer, communications, and the stimulator. Red elements are hardware components of the system, and blue boxes represent software components.

The system is designed to intervene when an apnea event is detected. This requires a transducer capable of converting the patient's breathing into an electrical signal, apnea event detection software, and a stimulator capable of providing a sensory stimulus to the patient when the system detects an apnea event. Analysis of breathing and control of stimulation is accomplished through the use of microcontrollers. These are programmed to look for a period in which a patient does not take a breath for 12 seconds (adjustable). Once such an event is detected, the belt microcontroller signals the microcontroller present in the stimulator module to fire. Once the stimulator delivers a stimulus to the region of sensitivity where the electrodes are placed, the brain stem is expected to return breathing functionality. If initial stimuli are unsuccessful, more powerful stimuli are delivered in successively smaller timeframes in order to attempt to restore breathing to the user.

III. Hardware Design

A. Transducer Belt: Signal Acquisition

The transducer gives a changing voltage signal as the subject breathes. This is facilitated through the use of a resistive Images Scientific 2" Flexible Stretch Sensor [9]. As the user's abdomen moves up and down during sleep, the motion causes the length of the resistive element woven into the belt to change. The change in length is translated into a change in the resistance of the sensor, and this in turn is converted into a voltage measurement with a Wheatstone bridge circuit.

B. Transducer Belt: Signal Conditioning

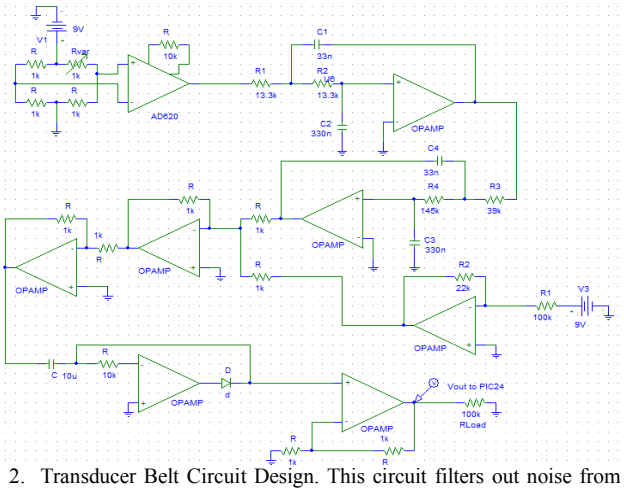

Fig. 2. Transducer Belt Circuit Design. This circuit filters out noise from the 60 Hz power lines, as well as conditions the transducer signal to be an acceptable input of the A/DC of the PIC24 microcontroller.

Figure 2 shows the layout of the signal conditioning circuitry. The signal is passed through a 4th order Butterworth low pass filter ($w_o = 30\ Hz$) in the Sallen-Key topology to smooth the signal and remove any interference from the 60Hz power lines. Once filtered, the signal must still be conditioned in order to prevent damage to the input pin of the PIC microcontroller. An offset of -2 V is added to the signal, and the signal is then clamped with reference to ground voltage. The clamp serves two purposes, safeguarding the PIC from negative voltages, from which it can only tolerate up to -0.3V [10], and removing the DC components from the signal, effectively giving the PIC a signal of 0V when the user has no abdominal motion. The conditioned signal is subjected to a final amplifier to spread the signal range between 0-3V for maximum variation in quantized signal values.

C. Communications

PIC24 microcontrollers are connected to both the transducer belt and the stimulator module. The transducer microcontroller uses an A/D converter to analyze inputs from the transducer. It sends command signals through a RF transmitter, operating at 400 MHz [11], in the belt circuitry to the PIC24 in the stimulator module. This microcontroller analyzes the command and then triggers a stimulus pulse. Encoding and decoding is performed by two separate PIC16 chips. The transmitter and receiver were selected as a kit from Rentron Electronics [12]. The kit was chosen solely for price constraints and simplicity. In future iterations of the system, alternative RF systems may be considered. All chips are placed in chip slots in order for easy replacement or reprogramming.

D. Stimulator Module: Core Stimulator

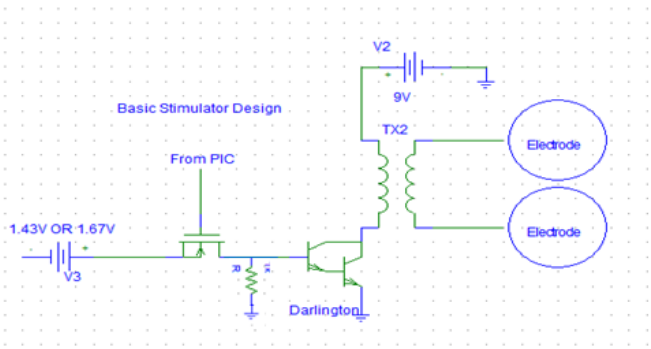

Fig. 3. Core Stimulator Design. This circuit enables sufficient voltages and currents to be generated in order to produce a perceivable sensory stimulus at the output of the electrodes. Signals from the PIC trigger the MOSFET to allow a signal to trip the Darlington pair, causing a stimulus pulse at the electrodes.

Stimulation requires a relatively high voltage to penetrate the impedance of the skin, and a minimum current of 5mA [13] to produce a perceivable stimulus. In order to generate the necessary voltages and currents, the stimulator is built using a transformer that is triggered by a Darlington pair, a design adapted from the thesis of K. Fernandes [14]. Square wave inputs to the Darlington pair causes it to open, and it acts as a current amplifier. This current amplification is necessary, as the transformer reduces the current of electrode side to scale up the voltage. This configuration increases the perceived intensity of a stimulus as voltage and/or frequency of the command signal to the Darlington pair are increased. The stimulator uses reusable electrodes to achieve minimal environmental impact, as well as simplify use of the device for the user.

E. Stimulator Module: Stimulator Control

The PIC24 can only output a constant voltage from its output pins, but it is desirable to have variable voltages to fire the stimulator with. This is accomplished by using a variable voltage regulator connected to an NPN MOSFET. The PIC24 triggers the MOSFET to open by providing a voltage across the gate, generating a square pulse at the pull-up resistor on the source end of the transistor. This in turn triggers the Darlington pair of the stimulator. The user can change the resistance of one of the resistors controlling the voltage regulator in order to tune the strength of stimulus pulses. The current prototype system has two selectable resistance values, generating 1.4 or 1.6V to be selected by connecting a jumper, however, future iterations of the design will use a potentiometer to allow greater flexibility in voltage selection.

F. Power Supply

The system is currently powered by the use of rechargeable Li-Polymer 9V batteries from IPower [15]. These batteries have a 500 mAh capacity. Two batteries are used to provide +-9V power to the transducer circuit, and one battery at 9V powers the stimulator module. The transducer circuit uses around 45 mAh (40 mA [10] from the PIC, 5 mA from the RF components [11] [16]), giving it roughly 11 hours of battery life. The stimulator uses a similar amount of current, with the exception of when the stimulator is firing. However, since the stimulator is not expected to be active regularly, battery life is still estimated to be above 10 hours for the stimulator system.

IV. Software Design

Limitations of the RF components being used caused the requirement of a PIC24 chip on both the transducer and stimulator ends of the system. On the transmitter end, the main purpose of the software is to determine whether the individual has entered into a pause in breathing that characterizes central sleep apnea. This is done by setting up an ADC that samples the incoming voltage signal from the transducer approximately 4 times a second. This sampling period may seem low at first, but considering that an average adult take 12-20 breaths per minute [17], 4 samples per second is more than enough to accurately sample the incoming time varying transducer signal. This sampling rate is well above the required Nyquist rate of (20 breaths per minute/60 seconds per minute) x2 = 0.66Hz. After the ADC samples, this value is placed into the first place of a global 2-element array. The next sample value is then placed in the second spot for the same array and this cycle repeats for as long as the program is running. After this, the two current values in this array are then compared to one another. If the difference between the two values is below a certain threshold value (0.1 in our case but is entirely dependent on noise and how much residual change in voltage occurs one a pause in breathing occurs), then a counter is incremented. This counter is used to keep track of how much approximate time has elapsed since the pause in breathing has started. Once the counter reaches a certain value, it signifies that the patient has not taken a breath in a significant period of time (12 seconds in our code), and then the code proceeds to output a square wave at 8 Hz with 4 zero to one transitions. This signal is then modulated and transmitted to the receiver and second microcontroller where the stimulator is turned on based on the criteria defined below. If this pulse does not result in the immediate restarting of the patients breathing, then the program reduces its wait time from 12 to 4 seconds, while increasing the number of zero to one transition from 4 to 8. If again this pulse is insufficient, then the wait time is reduced to 2 seconds and the number of zero to one transition from 8 to 12. If at any time, the patient's breathing is restarted, then the counter value is reset to zero, as well as the wait time and zero to one transition for the output wave. Figure 4 gives a visual outline of organization of the software.

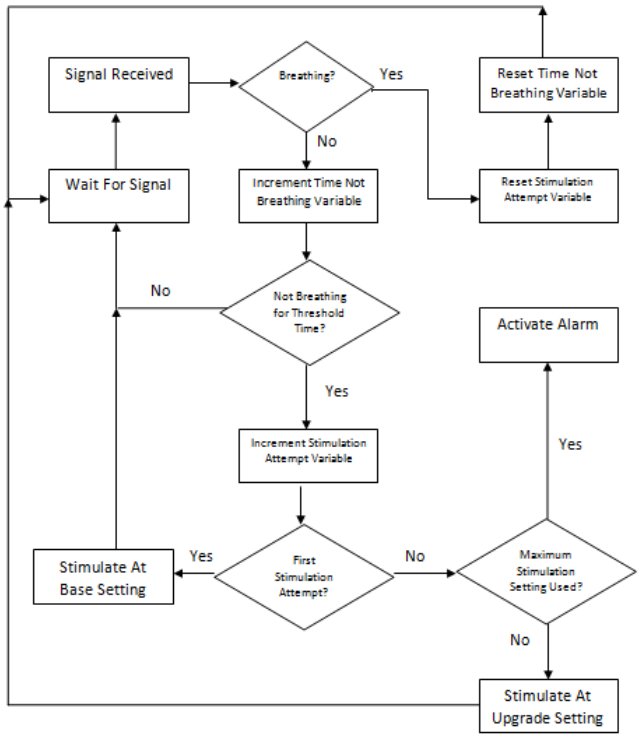

Fig. 4. Main software flowchart. The logic is implemented in the primary master microcontroller attached to the transducer module. The slave microcontroller on the stimulator module reads in a command signal signaling what stimulus it should send to the stimulator.

On the receiver end, the second microcontroller looks for the square wave output from the receiver and tries to count the number of zero to one transition via the ADC. Based on the number of transitions, this microcontroller will output a square wave at 15/30/45 Hz for 300/400/500 ms durations respectively that is used to turn the stimulator on. If the microcontroller counts 1-6 transitions then it outputs the 15 Hz pulse for 300 ms, if it counts 7-11 a 30 Hz pulse for 400 ms is outputted and if it counts 12 - 20, then a 45 Hz pulse for 500 ms is outputted.

V. Results

Initial tests of the overall system proved to be successful. The stimulator was first attached to a load resistor of 100KΩ resistor. The current was measured to be 15 mA and the voltage was measured to be approximately 70V. Figure 5 shows the command and stimulus pulses generated by the two PIC24 microcontrollers.

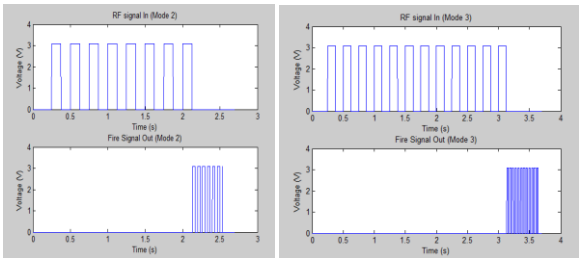

Fig. 5. Command and Stimulus Outputs of PIC24s. Note that the stimulator PIC will only fire its stimulus signal once it has finished receiving the entire command input. This is due to the use of an "input window" which closes once new input commands are no longer detected.

The system was tested with volunteers having electrodes attached to their palms or to the soles of their feet. Reactions were varied, with the majority of volunteers remarking that the stimulus would be sufficient to wake them in higher stimulus modes. Figures 6 and 7 show the completed system.

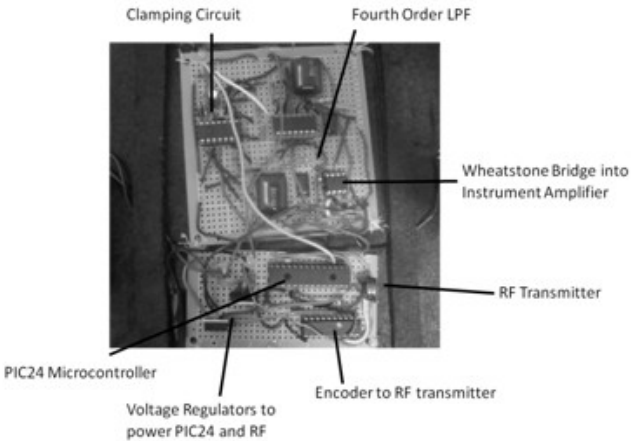

Fig. 6. Completed transducer belt circuitry. Refer to section III: Hardware design for a more in depth explanation of the various components labeled in the figure.

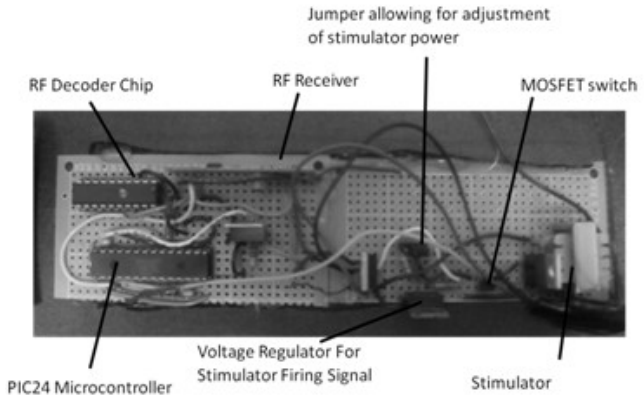

Fig. 7. Completed stimulator module circuitry. Refer to section III: Hardware design for a more in depth explanation of the various components labeled in the figure.

VI. Conclusion

The prototype device seen in Figures 6 and 7 is currently the extent of the project. The transducer circuit is mounted on a belt the patient wears on their abdomen, and is responsible for detecting apnea events and causing the slave microcontroller to produce a stimulus. The stimulator circuit is on standby until the slave microcontroller receives a signal from the transducer, at which point it produces a signal that triggers a stimulus to be fired by the stimulator circuit. This stimulus is expected to cause a patient to restart normal breathing. Once the necessary approvals have been obtained, the system will be tested to determine its overall effectiveness.

Acknowledgment

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