Design, Development, and Evaluation of a System to Obtain Electrodermal Activity

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Abstract

In recent years, activity trackers and other wearable electronic devices have gained popularity due to users' desire to monitor, measure, and track using various real-time features related to their fitness or health, including the number of steps they take, their heart rate, their heart rate variability (HRV), the users' temperature, their activity and/or stress levels, etc. One known technique for determining stress levels involves monitoring, measuring, and/or tracking electrodermal activity (EDA), which can be performed by measuring skin impedance or skin conductance. It has been shown in studies that in response to an environmental, a psychological, and/or a physiological arousal, users' skin conductance would increase. By measuring changes in the skin impedance or the skin conductance over time, metrics can be obtained relating to users' activity level, stress level, pain level, and/or other factor(s) associated with users' present psychological and/or physiological condition, allowing users or physicians to take appropriate steps to address their condition based on the obtained metrics.

The final goal of this article is to provide a useful physical system to investigate and finally estimate/quantify the stress level of a person.

Introduction

Stress is a physical, a mental, or an emotional factor that causes bodily or mental tension. Stresses can be external (environmental, psychological, or from social situations) or internal (illness or caused by a medical procedure). Stress can initiate the fight-or-flight response, a complex reaction of neurologic and endocrinologic systems.

The fight-or-flight response (also called the fight, flight, freeze, or fawn response in post-traumatic stress disorder, hyperarousal, or the acute stress response) is a physiological reaction that occurs in response to a perceived harmful event, attack, or threat to survival.

The reaction begins in the amygdala, which triggers a neural response in the hypothalamus. The initial reaction is followed by activation of the pituitary gland and secretion of the ACTH hormone. The adrenal gland is activated almost simultaneously and releases the epinephrine hormone.

The release of chemical messengers results in the production of the cortisol hormone, which increases blood pressure and blood sugar, and suppresses the immune system. The initial response and subsequent reactions are triggered in an effort to boost energy. This boost of energy is activated by epinephrine binding to liver cells and the subsequent production of glucose. Additionally, the circulation of cortisol functions to turn fatty acids into available energy, which prepares muscles throughout the body to respond. Catecholamine hormones, such as adrenaline (epinephrine) or noradrenaline (norepinephrine), facilitate immediate physical reactions associated with a preparation for violent muscular action.

However, under constant demand, the stress system becomes chronically active and can have damaging effects on the health of an individual.

There are many kinds of illnesses caused by stress that affect both the body and the mind.[1] These will be mentioned later in the article.

Methods

There are different methods to detect and determine the stress level. The most important methods are: measuring cortisol level, obtaining heart rate variability, or obtaining the electrodermal activity.

Measuring Cortisol Level

Cortisol is a steroid hormone in the glucocorticoid class of hormones and is produced in humans by the adrenal cortex, within the adrenal gland. It is released in response to stress. Thus, measuring the cortisol level is considered the gold standard method to quantify the stress level.[2] However, this technique has two important issues. One of the issues is the delay between the threat and the variation in the cortisol level, which may be up to 15 minutes. The second and most important issue is that stress levels should be obtained continuously in order to detect the threats and stress situations in the user's daily life. Thus, this method is too complex, expensive, and unfriendly for anybody and, therefore, cortisol measurement is not a suitable method for general use.

Obtaining HRV

HRV is the physiological phenomenon of variation in the time interval between heartbeats. It is measured by the variation in the beat-to-beat interval.[3]

Currently, there are many devices on the market that can measure heart rate. The resolution of these devices is one beat per minute (bpm) in the best case. This resolution is good enough in many applications. However, the required resolution of HRV for stress assessment is 10 or 100 times higher. This means that the sampling frequency and algorithm complexity must be greater and, hence, the power consumption of the system can became too much for a wearable product or a 24/7 application.

Obtaining EDA

EDA is an indirect measure of neurally mediated effects on sweat glands' permeability, observed as changes in the resistance of the skin to a small electrical current or as differences in the electrical potential between different parts of the skin.[4]

EDA presents more advantages than the other techniques in terms of power consumption, ergonomics, and circuit size.

System Description

The objective of this research is to develop a useful tool to investigate and estimate the stress level of a person. The stress level of a person is not constant and it depends on the threats perceived by the person. Those threats are perceived differently by each person and there are many factors that can make a simple event for a person an enormous threat for another. It is not useful to carry out a stress test in a hospital in order to determine the stress level of a person, since these threats appear in the normal life of the patient. Therefore, it is necessary to develop a system that allows us to estimate the stress level of a person during his or her normal life. Thus, this system must be noninvasive, user-friendly, and wearable. Finally, it must be able to work for several days without being recharged or replaced.

The requirements for the final device imply the system must be:

- Battery operated, since it must be wearable
- Low power, since the patient must be monitored for several days
- Reduced size, since it must be wearable and user-friendly
- Low cost, since if it is too expensive, the solution will not be implemented in any consumer device
- Compliant with safety regulations

In order to ensure the system is nonintrusive, the recording site must be taken into account. The best placement for the electrodes is the top of the wrist, since this results in the device being: noninvasive, user-friendly, and simple from the mechanical point of view. However, the quality of the signal is not as good as the EDA signal obtained from other body locations, such as the medial phalanx in the index and middle fingers.[5]

Once the electrodes' placement to obtain the EDA signal is decided, it becomes obvious that the final (target) system will present the form of a smartwatch or a similar device. At this point, the next specification to determine is the area that can be used by the EDA circuit. Several smartwatches were analyzed and various vendors were consulted about this topic in order to determine this parameter. The conclusion was the maximum area of the EDA circuit should be less than 5 mm × 5 mm.

The power consumption of the EDA circuit is the third parameter to set. This parameter is key to ensure the system will be able to record the EDA signal during several days without recharging or replacing the device. The battery's capacity for different smartwatches and the power budget of some possible commercial systems are obtained. The target for the power consumption obtained after this investigation is fixed at a maximum average consumption of 200 µA.

Finally, the last specification to determine is the cost. However, this is not determined at this stage, since there are several factors that can affect the final cost of the device. The circuit topology and components are selected to ensure a reasonable cost for the final solution.

Hardware Design

This section describes how the circuit topology, range to measure, and resolution are determined.

One of the key decisions is to determine the topology of the circuit. Basically, there are two methods to measure an impedance. The system can apply current and measure the voltage across the impedance, or it can apply voltage and measure the current across the impedance. Besides, these signals can be dc or ac.[6] It is important to analyze the advantages and disadvantages of each method.

There are dozens of circuits that measure ac and each one has its pros and cons. However, in order to accomplish the restrictions in performance, cost, and area, the following solution is considered as the best option.

The final decision is to use an ac voltage source as the excitation source and measure the current through the patient's body to determine the skin conductivity. This solution avoids high voltages over single sweat glands, eliminating the danger of sweat gland damage and allowing the compliance of the IEC6060-1 standard. The ac signals eliminate the problem of electrode polarization.[7]

The current that must be measured needs to be digitalized, stored, and analyzed. It means the circuit will require an analog-to-digital converter (ADC). As most ADCs convert voltage and not current, the current through the patient's body needs to be translated to voltage. This is carried out by a transimpedance amplifier (TIA). The noise specifications, size, and power consumption are three critical characteristics to choose the best operational amplifier, which will be used to implement the TIA.

Once the topology of the system is decided, the next step is to determine the range and resolution of the system under development.

Problems for the amplification of the EDA signal mainly stem from its wide range and the required high resolution. Typically, a skin conductance device must cover a range from 0 µS to 100 µS and it must also be able to detect 0.05 µS fluctuations. This resolution can be achieved using an ADC with at least 12-bit resolution. Regarding the resolution, the target in this project is 0.01µS, and, therefore, an ADC with 14-bit or 16-bit resolution is required.[8]

In order to get a resolution of 0.05 µS within a range of 100 µS while complying safety regulations, these blocks are required.

- An ac voltage source
- Protection elements to ensure compliance with IEC6060-1
- An electronic circuit to measure the current flowing through the patient's body

Variations in the ambient temperature and skin temperature can produce changes in the EDA signal.[9] Thus, it would be interesting to acquire the ambient temperature and skin temperature, too. It can be carried out by a simple thermistor plus several discrete components and an ADC.

Finally, power consumption is critical in this circuit. In order to reduce it and ensure the system is only activated when a new measurement is required, a power management unit must be also integrated. This block must be easily controlled by the main microcontroller and it has to supply all the EDA measurement circuit. Figure 1 shows the complete block diagram.

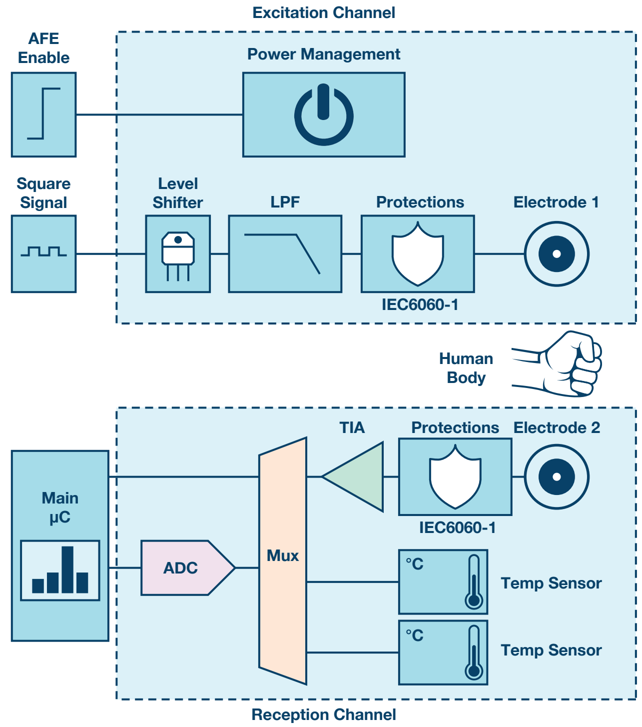

Figure 1. System block diagram.

In the following sections we will determine the best components for this application.

Power Management Unit

The decision is to use the ADP151 family to implement the power management unit due to several good features, and because its package and noise level are excellent for this application.[10]

Level Shifter

There are many ways and a broad range of integrated circuits to implement a level shifter. However, the area and price of those integrated circuits do not accomplish the restrictions of this project. Thus, the level shifter in this circuit was implemented by discrete components. Basically, it is formed by a transistor, DMN2990UFZ,[11] and a resistor.

Low-Pass Filter and TIA

In order to implement the low-pass filter and the TIA, the ADA4505-2ACBZ is used as it has excellent power consumption, small size, and very low input bias current.[12]

ADC

The ADC that accomplishes all the system requirements is the AD7689BCBZ. This powerful ADC includes the voltage reference that can be turned off when it is not used in order to reduce the power consumption.[13]

Finally, in order to ensure the area constraint can be achieved, the minimum number of components and functionalities have been included and the smallest packages for all the components have been picked. Figure 2 shows the layout and size of this system.

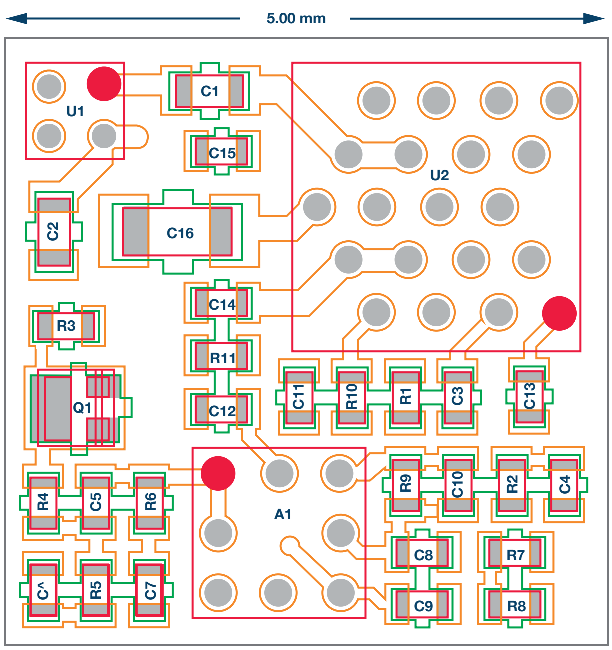

Figure 2. EDA discrete circuit layout.

Software Design

As mentioned previously, the system needs to generate an excitation signal in order to measure the conductivity of the skin. This excitation signal is an ac signal, and the two parameters, which can be extracted from an ac measurement, are the amplitude of the signal and the phase delay between the excitation signal and the acquired signal. The most important one is the amplitude, and there are several ways to obtain this parameter from an ac signal. However, the best method to obtain the amplitude in this system is to implement a discrete Fourier transform (DFT).[14]

The DFT can also be considered like a bank of filters and the level of attenuation is directly proportional to the number of samples, and the position of the maxima depends on the excitation signal.

At this point, a good argument would be to use a big number of samples (N) to implement the DFT since it would improve the SNR. However, the power consumption of the DFT (if implemented directly) is proportional to the number of samples and we will need more power as we acquire more samples. This means that there is an important trade-off between the number of samples and the power consumption.

Another important parameter is the ratio between the sampling frequency and the excitation frequency. The equation that implements the DFT is very simple if the sampling frequency is 4× the excitation frequency. In this case, the complex equation involving floating-point multiplications turns into additions. Multiplications can be bearable if the available processor is a DSP or a Cortex®-M4. However, this can be an important problem when the calculation must be implemented in a Cortex-M0. Compare Equation 1 to the filter notation of a single-point DFT calculation for a 100 Hz bin (F_{CENTER}) when the sampling frequency (F_S) is 400 Hz and 500 Hz.

$$F_{CENTER} = 100\ Hz,\ F_S = 400\ Hz,\ N{=}16:$$
$$\begin{aligned} H(z) = 1 &- (1i\,z^{-1}) - z^{-2} + (1i\,z^{-3}) + z^{-4} - (1i\,z^{-5}) - z^{-6} \\ &- (1i\,z^{-7}) + z^{-8} - (1i\,z^{-9}) - z^{-10} + (1i\,z^{-11}) + z^{-12} \\ &- (1i\,z^{-13}) - z^{-14} + (1i\,z^{-15}) \end{aligned}$$

$$F_{CENTER} = 100\ Hz,\ F_s = 500\ Hz,\ N{=}16: \tag{1}$$
$$\begin{aligned} H(z) = 1 &+ (0.38 - 0.92i)z^{-1} - (0.7 + 0.7i)z^{-2} \\ &- (0.92 - 0.38i)z^{-3} + (1i)z^{-4} + (0.92 + 0.38i)z^{-5} \\ &+ (0.7 - 0.7i)z^{-6} - (0.38 + 0.92i)z^{-7} - z^{-8} \\ &- (0.38 - 0.92i)z^{-9} + (0.7 + 0.7i)z^{-10} \\ &+ (0.92 - 0.38i)z^{-11} - (1i)z^{-12} - (0.92 + 0.38i)z^{-13} \\ &- (0.7 - 0.7i)z^{-14} + (0.38 + 0.92i)z^{-15} \end{aligned}$$

Once the technique to apply and the ratio between the excitation frequency and the sampling frequency are clear, the next step is to determine the excitation frequency.

The excitation frequency must be as low as possible to ensure the current will flow through the patient's skin and it will not penetrate into the body.[15] Therefore, the excitation frequency must be smaller than 1 kHz. It must also be mentioned that the main source of noise in this application is the 50 Hz/60 Hz noise due to the power mains.

$$f_{zero} = \frac{F_S}{N} \times k = \frac{4 \times f_{exc}}{N} \times k \qquad k = 0 \ldots (N-1) \tag{2}$$

Equation 2 shows that each component of the DFT, X(k), nulls the contribution of the spectral components of the form $n \times F_S/N$ where n = 0, 1, 2, and through N – 1, except for when N = k. By properly defining the excitation frequency we may cancel the contribution from the 50 Hz noise source. However, a high frequency cannot be used due to the previous arguments. Thus, a good trade-off is 100 Hz, although we may capture the harmonics of the main's interferer.

If the excitation signal is 100 Hz and the sampling frequency is 400 Hz, the zero at 50 Hz appears when N is equal to 8, 16, and 32. We must also keep in mind the number of samples must be as small as possible to minimize power. Thus, a good trade-off is to use 16 samples to implement the DFT. The number of samples can be increased in order to improve the SNR if it is required. Of course, if the noise is the 60 Hz noise instead of the 50 Hz, the sampling frequency should be 480 Hz and the excitation frequency should be 120 Hz. The frequency response is shown in Figure 3 and the mathematical equation, which only involves addition, is shown in Equation 3.

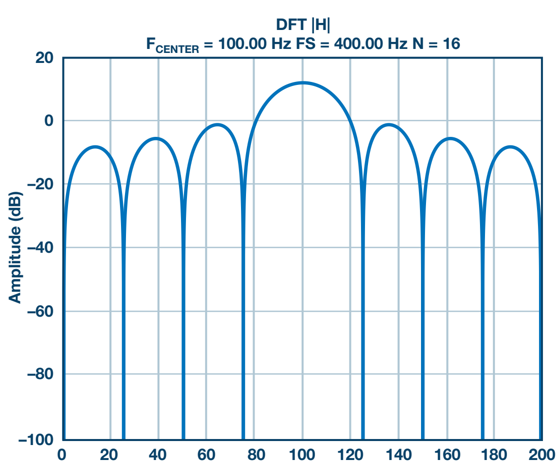

Figure 3. DFT can be considered a bank of filters. This is the DFT frequency response with 16 samples, a sampling frequency 400 Hz, and a center frequency of 100 Hz with a rectangular window.

$$\begin{aligned} X(k) = &\sum_{n=0}^{\frac{N}{4}-1} [x(4n) - x(4n+2)] + \\ &\sum_{n=0}^{\frac{N}{4}-1} [x(4n+3) - x(4n+1)] \times j \end{aligned} \tag{3}$$

Mechanical Design

An evaluation system was developed to test and prove this proposed solution. The platform is composed of the main sensors required in EDA measurements and some other indispensable features. Movement and temperature may affect the skin impedance measurement.[9, 16] Therefore, signals capturing motion and temperature are also obtained.

The system also includes a battery charger to recharge the LIPO battery used in this platform. This device requires a battery with high capacity, as we want to enable 24 hour acquisitions. Impedance, temperature, and acceleration measurements are saved in a file which is stored in a micro SD card or the data can be sent by Bluetooth® low energy to a tablet or PC. Figure 4 shows the evaluation platform.

Figure 4. EDA evaluation platform. ADI watch GEN II.

Results

SNR Study

A mathematical analysis is carried out to ensure the required resolution could be achieved with the noise of the selected components and the bandwidth of the system. However, this feature has to be checked with actual measurements. In order to do it, the prototype system is used to measure several resistor networks to check functionality. The study consists of obtaining several measurements of the same resistor network to check the repeatability and, therefore, obtaining the system's accuracy. In this test, 100 measurements are performed for each network and the maximum error is obtained by subtracting the minimum value to the maximum value of the obtained results. The error is always equal to or smaller than 0.01 μS.

Once the accuracy of the system is validated, the next step is to check the system's linearity. In order to carry out this experiment, the prototype is connected to a programmable resistance substituter and the range from 10 kΩ to 500 kΩ in steps of 1 kΩ is evaluated. The R^2 of the system is 0.9999992.

Power Consumption Study

The EDA system is formed by a state machine with different statuses in order to obtain the patient's skin conductivity and ensure the minimum power consumption. Initially, in status one (S1), the EDA's AFE is turned off and just the microcontroller and the accelerometer are on. The average current consumption is 139 μA. After approximately 150 ms, the EDA AFE is turned on, the square signal is generated by the MCU, and filtered by the LPF. The ADC reference is turned off during this stage (S2) because the signal is not stable yet. Six cycles are required to ensure the signal is stable and, in the worst case, the average current consumption in S2 is 230 µA. The ADC reference is turned on in the S3 and the system waits for 10 ms to ensure the reference is stable—the average current consumption in this stage is 730 µA. The system acquires four samples during four cycles in order to obtain 16 samples to implement the DFT in S4. The power consumption in this stage is 880 µA. The DFT is implemented in stage S5. The accelerometer data is also obtained in this status, and the current consumption in this stage is around 8 mA. Figure 5 shows the power consumption of the system. This study proves the average power consumption of the EDA AFE requires less than 170 µA.

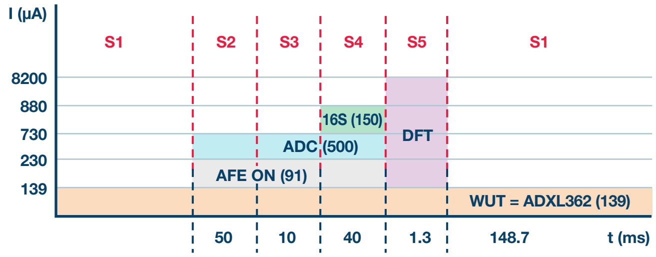

Figure 5. Power consumption analysis.

Experimental Tests

At this point, the system has been electronically evaluated—hence, the next step is to correlate the EDA circuit with a reference. In this case, the E4 platform from Empatica is used as the reference due to its good performance.

Once the reference is decided, we decide the test that must be carried out to see a variation in the EDA signal. The selected test was the relaxation-stress test. This test is formed by two steps: the first step is a relaxation exercise and the second step is a stress exercise.

The relaxation exercise consists of 10 minutes of paced breathing to reach a relaxed state. The stress state is achieved by playing the color-word-sound game. In this application, the user listens to a color and sees the text of a color, which is illustrated with a color. Either the audible color, the texted color, or the illustrated color can be the same or different. As the reader can observe in Figure 6, there is a sentence that can be:

- Choose color
- Choose sound
- Choose word

Depending on the message of the sentence and the audible, text, or color, the person under test will have to press the correct button. The user must respond before the progress bar finishes.

If the user does not respond in that time, or if the response is wrong, the score value will be decremented. If correct, the value will be incremented. Finally, the buttons' positions are swapped.

There are several settings that can be modified in this application to modify the level of the experiment (level of stress).

Figure 6. Color-word-sound test application.

Theoretically, the skin conductance should decrease during the relaxation task and it should increase during the stressful activity. Peaks or spikes should be observed during the stressful activity. The variation in the dc level corresponds to the tonic response to the stressor. The observed peaks in the stressful activity are considered the phasic response, which does not appear during the relaxation task.

Once the procedure to obtain a clear variation in the EDA signal and the expected response have been exposed, the next step is to carry out an experiment to compare the performance between our EDA solution and the Empatica E4 platform. In order to compare them, both devices are worn simultaneously while the person is doing the test. The Empatica solution is worn on the right hand and the system under test is worn on the left hand. This means the expected signal must be similar but not exactly the same, since each device was worn on different arms and the measurement location is not exactly the same, because the Empatica obtains the EDA signal from the bottom of the wrist while our solution obtains the EDA signal from the top of the wrist. The obtained signals by both devices are very similar as shown in Figure 7. This experiment was repeated several times with different patients in order to validate the system.

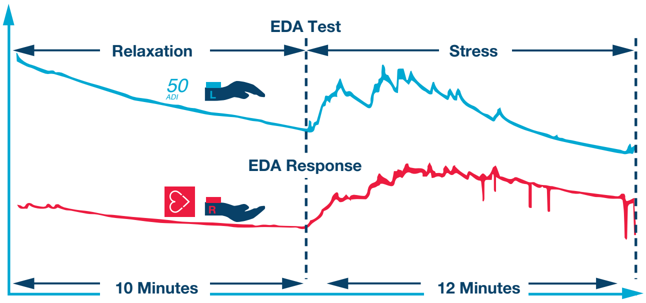

Figure 7. Relaxation stress test with system under test in the left hand and the reference device in the right hand.

Conclusion

This EDA circuit is a smart solution to obtain skin's conductivity. Its average current consumption and size ensure its integration in any smartwatch or similar platform. The device achieved the expected performance as it measures the skin's conductivity in a wide range with a high resolution. The EDA circuit design ensures its compatibility with any kind of electrodes, since the polarization and half-cell potential effects are avoided. Besides, the IEC6060-1 requirements are fulfilled.

In order to evaluate and test the features of the circuit, a prototype was designed. The system was designed to obtain the EDA signal, in combination with the skin temperature, ambient temperature, and motion, during 24 hour sessions with no recharge, and to store the information or transmit it wirelessly in real time. Therefore, this platform can be used to collect EDA data from different people in different situations in any moment of their lives. Finally, this information can be used to develop algorithms that can detect, estimate, or predict the stress level of a person.

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