Contactless Electrical Bioimpedance System for Monitoring Ventilation
A Biodevice for Vehicle Environment

Raúl Macías Macías, Miguel Ángel García González, Juan Ramos Castro, Ramon Bragós Bardia and Mireya Fernández Chimeno

Department of Electronic Engineering, Universitat Politècnica de Catalunya, Campus Nord, Edifici C-4 08034, Barcelona, Spain

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Abstract: Nowadays, automotive companies are focused in improving road traffic safety. For that, not only the vehicle performance is improved but also the driver behavior is monitored. This could be done in many ways. One of them is to monitor a specific physiological parameter using a biodevice. That device should be reliable enough to use in a very noisy environment like a vehicle is. Furthermore, because long-term monitoring is required, any invasive and annoying method should be avoided. Therefore, an electrical bioimpedance device capable of monitoring driver ventilation using several textiles electrodes has been designed and implemented.

1 INTRODUCTION

In recent years one of the main goals of the automotive industry is to improve the road safety. Because of most of traffic crashes occur during the appearance of non-appropriate states for driving, *e.g. drowsy driving or drunk driving* (Anund et al., 2008), apart from improving the vehicle performance, monitoring the driver behavior is also required. To achieve that, several systems are being tested. These systems can be mainly classified on three types. First type is based on driving performances *i.e. unintended lane departures, steerings and brakes*. The second one is based on camera systems that detect the percentage of eye closure (PERCLOS), head movements and blinkings. Finally, the third type is based on recording biomedical signals. In (Michail et al., 2008), signals from electroencephalography (EEG), electrocardiography (ECG) and heart rate variability (HRV) are used. On the other hand, electrooculography (EOG) and ventilation are used in (Lal and Craig, 2001) and in (Folke et al., 2003), respectively.

Focusing on the third type, regardless of the physiological parameter to be measured, any biodevice should fulfill three requirements at least. Firstly, the biodevice must be capable of recording signals in a very noisy environment. In a vehicle, there are not only artifacts produced by the car engine but also artifacts caused by other reasons like body motion or the state of the roads. As for the second feature, a long-term monitoring system is required because the appearance of non-appropiate states while driving is a slow process. Moreover, the device should also be non-invasive and non-annoying to allow the driving as comfortable as possible. Therefore, the use of hospital devices is not recommended and the design of new biodevices is required.

Thus, this paper shows a new biodevice suitable for automotive applications. This device consists of an electrical bioimpedance (EBI) system capable of monitoring the ventilation, and also the heart rhythm, using textile electrodes. These electrodes are placed on the steering wheel and also in the car seat. In addition, this paper also shows some results according to some parameters such as the electrode configuration, the frequency of the injected signal and the clothing thickness.

2 SYSTEM

As mentioned above, the biodevice is based on an instrumentation system of EBI. This allows to monitor signals from the driver by textiles electrodes. The device is designed following the guidelines shown in (Riu et al., 2009). In addition, in order to avoid the impedance of the electrodes, the EBI system is based on the four-wire method proposed by (Schwan and Ferris, 1968).

Thus, as shown in figure 1, the biodevice can be

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divided into three main blocks:

- Signal Generator (GEN).
- Analog Front-End (AFE).
- Demodulator and Acquisition (DEM).

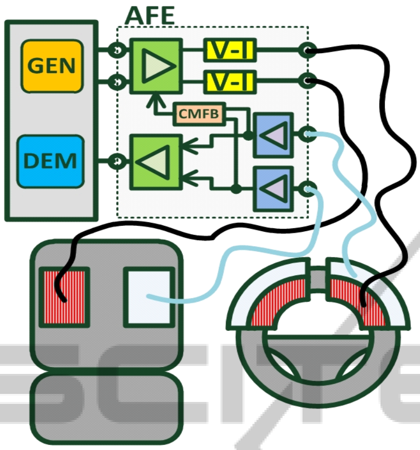

Figure 1: A block diagram of the EBI device. The striped areas are the possible placements of the driving electrodes. In light color, the possible placements of the sensing electrodes.

2.1 Signal Generator

Signal generation can take several forms, e.g. from a simple linear oscillator or digital clock to a Direct Digital Synthesizer (DDS) able to produce sinusoidal waveforms or arbitrary waveforms in a wide range of frequencies and amplitudes. In this case, and because of hardware limitations, the selected option is to generate by a microcontroller, PIC18F1320, an adjustable amplitude single tone waveform of 62.5 kHz.

Later, this signal is used also as the reference signal in the demodulator block.

2.2 Analog Front-end

Once the signal is generated, this is sent to an AFE. Basically, the AFE consists of two main stages. In the first stage, the AFE injects an excitation signal through a pair of driving electrodes. In the second one, a pair of sensing electrodes are used to measure the voltage difference which is related to the properties of the tissue.

2.2.1 Current Injection Stage

The excitation signal is sent to a differential-differential amplifier, AD8138. However, instead of applied directly the voltage of these two outputs to the driving electrodes, each one is used as an input of a voltage-current (V-I) converter based on a second-generation current conveyor (CCII). Thus, the V-I converter acts as a voltage-controlled current source (VCCS), (Bragos et al., 1994). In this way, using current driving instead of voltage driving achieves a current limiting mechanism and reduces the possible nonlinearities. So the guidelines of safety risks provided by the IEC-60601-1 standard can be fulfilled. In this case where a 62.5-kHz frequency current is injected, the current limit is established in 6.250 mA.

In addition, as there are filter capacitors to avoid the flow of the Direct-Current (DC) current to the body, in this stage a DC feedback of the CCII is also required to avoid saturation problem.

2.2.2 Voltage Sensing Stage

In the voltage sensing stage, a differential to single ended voltage conversion is done by a wideband differential amplifier. However, before this conversion, the voltage difference between the pair of sensing electrodes is measured by a pair of high-impedance buffers. These buffers are used because of their input impedances are higher than the input impedance of the differential amplifier. Furthermore, these buffers also allow to measure the common-mode voltage without disturbing the signal quality.

In addition, as in the current injection stage, filter capacitors are also required. Thus, to avoid the saturation of the amplifiers the polarization currents of the amplifiers should be as low as possible.

2.2.3 Common-mode Feedback Block (CMFB Block)

Usually there is not a perfect isolation between the current injection stage and the voltage sensing stage. Thus, due to these unbalanced conditions a common-mode voltage can exist. To reduce this voltage a feedback circuit with the appropiate negative open loop gain is required. Furthermore, this feedback circuit should also maintain the stability of the system.

2.2.4 Active Shielding

In order to reduce interferences from external electromagnetic fields and crosstalk between the driving electrodes and the sensing ones, shielded cables are used. The shield of these cables is connected to a circuitry. This circuitry drives the shield to a voltage that is equal to the voltage in the internal wire. Due to oscillation problems could appear at high frequencies, a filter capable of reducing the gain below one at high frequencies is also used at the input of the active shielding circuitry.

2.3 Electrodes

As mentioned above, the electrodes should be as no-invasive and no-annoying as possible for the driver. Therefore, using standard metal electrodes seems to be not the better option. In addition, as cited in (Wheelwright, 1962),during long-term monitoring, the hidrogel used with this kind of electrodes can cause irritation and allergy problems.

So, in this system instead of using standard metal electrodes, electrodes made of textiles, also called textrodes, are chosen. In this way, not only irritation and allergy problems are solved but also a higher comfort for the driver is achieved. However, the main drawback of the textrodes is that the electrode impedance, Z_{ep}, shows a strong capacitive behavior, (Beckmann et al., 2010). In addition, as the textrode is not directly in contact the skin, this capacitive behavior depends on the exerted pressure and factors related to the clothing of the driver like material, thickness or number of layers.

2.4 Demodulator & Acquisition

Although there are several demodulation techniques, a switching demodulator is used. Switching demodulators are based on a switch controlled by a square signal. The frequency of this square signal is the same that the signal generated by the microcontroller in the signal generator block. After the switching demodulator, the signal is driven to a third-order Sallen-Key low-pass filter (LPF). Then using this output signal from the LPF, the measured voltage is acquired. In addition, by a high-pass filter (HPF) and a basic circuitry, the relative variations of the measured voltage are also amplified and acquired. These voltage variations should be amplified before recording because of their low amplitude and also the poor accuracy that the 10-bit Analog-to-Digital Converter (DAC) of the microcontroller can provide. Finally, the acquired data are sent from the microcontroller to a computer by a mini USB-Serial UART development module. Thus, any software such as Matlab or LabVIEW can be used later to process and to estimate the impedance value.

3 MEASUREMENTS

To check that the biodevice works properly, several measurements are carried out. These measurements can be classified into three groups according to:

- Comparison to a reference signal.
- Configuration of electrodes, i.e, the placement of the driving and sensing electrodes in the car seat and steering wheel.
- Influence of the thickness of clothing.

Note the measurements were done in a simulation environment where there are no interferences caused by the state of the road or the car engine vibrations.

3.1 Comparison to a Reference Signal

In this group, several subjects are monitored by the designed device and also by a commercial one made by BIOPAC Systems. The commercial device acquires at a sampling frequency of 1 kHz the ventilation signal using a piezoresistive thoracic band. Then, this signal is used as reference signal to verify the correct operation of the designed device.

It is worth mentioning that in this case, only the proper behavior of the AFE is checked in fact. Instead of using the signal generator block and the demodulator block mentioned above, a National Instruments Data Acquisition (DAC) module is utilized. By this module, a single frequency sine wave of 300 kHz is generated and In-phase Quadrature (IQ) demodulation is done to obtain the real and imaginary part of the signal at a sampling frequency of 25 Hz. Finally, using a Labview application, the magnitude and the phase of the estimated impedance are saved. Note that instead of generating a signal of 62.5 kHz, a signal of 300 kHz is applied. There are two reasons to apply a higher frequency. First, using this DAC module, the hardware limitation is less strong as the one imposed by the generator and the demodulator blocks described above. Second, the higher the frequency a better response of the system is achieved because of the capacitive behavior of the textile electrodes.

3.2 Configuration of Electrodes

In the second group of measurements, the biodevice is checked according the placement of electrodes. Thus, whereas the frequency of the injection signal is fixed to 62.5 kHz, the place of driving and sensing electrodes is changed, giving three configurations:

- Steering Wheel-steering Wheel Configuration.
- Steering Wheel-back Seat Configuration.
- Back Seat-back Seat Configuration.

In the steering wheel-steering wheel configuration, a driving electrode and a sensing electrode are in contact with the right hand of the driver. In the same way, the other pair of driving-sensing electrodes and the left hand are also in contact.

On the other hand, in the second configuration, whereas a driving and a sensing electrode remain in the steering wheel, the other driving and sensing electrode are moved to the upper half of the back seat.

Finally, in the back seat-back seat configuration, instead of using the 4-wire technique, the 2-wire technique is carried out because of both textile electrodes on the back seat act as driving and sensing.

3.3 Influence of the Thickness of Clothing

In the last group of measurements, the relationship between the clothing and the measured signals is tested. Therefore, using the steering wheel-back seat configuration, the ventilation of a subject is monitored under the following states according to the clothes:

- Thin t-shirt.
- Thin jacket over thin t-shirt.
- Thick sweater over thin t-shirt.

4 RESULTS

As in previous section, the results are discussed based on the three kinds of measurements.

4.1 Comparison to a Reference Signal

As mentioned above, the signal acquired by the thoracic band acts as a reference to check the signal from the designed biodevice. Thus, the biodevice works properly if the measured signal fits to the reference, i.e. for the same period of time, the exhalation-inhalation ratio is the same in both signals.

For each volunteer, two different configurations are tested. In the upper graphs of the figures 2, 3 and 4, as a driving electrode and a sensing electrode are in contact to the left hand, the second driving and the second sensing electrode are placed in the right and left side of the back seat, respectively. On the other hand, in the bottom graphs whereas the electrodes on the back seat remain at the same point, both electrodes on the steering wheel are moved to the right side.

Note that for all cases except one (bottom graph in figure 4), both signals, from the bioimpedance device and from the thoracic band, match up. The special case can be due to the lack of contact between any textrode and the volunteer.

Furthermore, whereas the figures 2 and 4 show a normal respiration rate, i.e. between 12 and 20 breaths per minute in adults and in normal conditions, in the figure 3 a slower respiration rate, around 6-7 breaths per minute, can be observed.

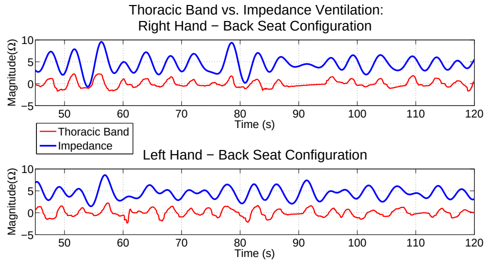

Figure 2: Comparison between the Thoracic Band and the Bioimpedance Device for the first volunteer. (Top) Configuration where both driving electrodes, back seat and steering wheel, are in the right side of the body. (Bottom) Configuration where the driving electrode of the steering wheel is in the left hand and the other driving electrode is in the right side of the back. In both plots, the upper line is related to the bioimpedance device and the bottom one comes from the thoracic band.

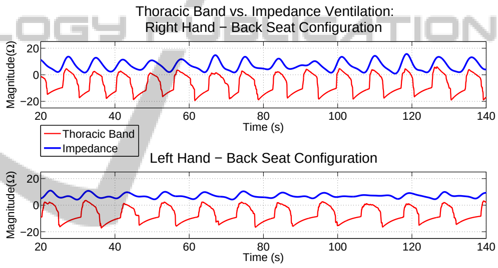

Figure 3: Comparison between the Thoracic Band and the Bioimpedance Device for the second volunteer. (Top) Both driving electrodes are in the right side of the body. (Bottom) The driving electrode of the steering wheel is in the left the other driving electrode is in the right side of the back.

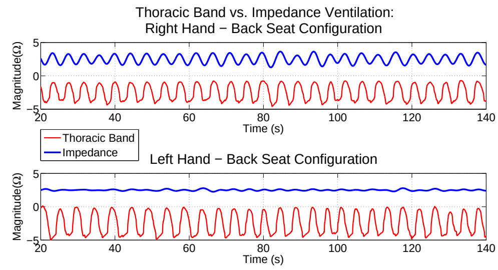

Figure 4: Comparison between the Thoracic Band and the Bioimpedance Device for the third volunteer. (Top) Both driving electrodes are in the right side of the body. (Bottom) The driving electrode of the steering wheel is in the left the other driving electrode is in the right side of the back.

4.2 Configuration of Electrodes

In this group of measurements, the influence of the placement of the electrodes in the measured signal is checked. Then, as mentioned above, three configurations are tested. In any configuration, the same test is done. The test consists of a two-minute monitoring and, around the last 30 seconds, five deep breathing are taken. It is worth mentioning that instead of using the National Instruments DAC module, in this group of measurements, and in the group below, the signal generation block and the demodulation block are based on a microcontroller which gives an injection signal of 62.5 kHz.

As shown in figures 5, 6, 7 and 8, three signals are plotted. The middle one is the raw signal measured by the bioimpedance device and without processing. Note that this signal is based on two components: a low-frequency component, between 0.1 Hz and 0.3 Hz, and a high-frequency component, over 1 Hz. Then, in the figures the upper signal is related to the low frequency component of the raw data and the bottom one is related to the high frequency component. Furthermore, the low frequency signal and the higher one are also related to the ventilation and the cardiac rhythm, respectively.

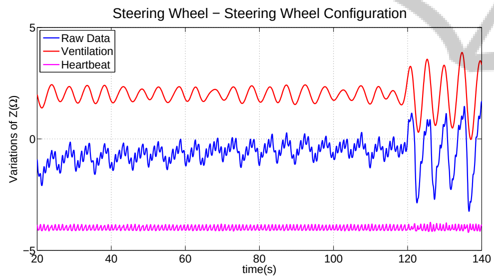

Figure 5: Steering Wheel - Steering Wheel Configuration. (Middle) The raw data obtained from the bioimpedance device. (Top) The processed data after applying a simple software band-pass filter, between 0.1 Hz and 0.3 Hz, to obtain the ventilation signal. (Bottom) The processed data after applying a simple software high-pass filter, over 1 Hz, to obtain the signal related to the cardiac rhythm.

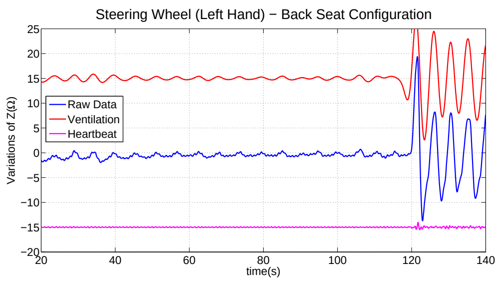

Figure 6: Steering Wheel - Back Seat Configuration with a driving electrode in the left hand and the other in the right side of the back. (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the cardiac rhythm.

Checking the figures 5, 6, 7 and 8, a first issue can be observed. As in figures 5 and 7, the high frequency component is noticed easily, in figure 8 this component is insignificant. Therefore, either it is not possible to measure the signal related to the cardiac rhythm using a 2-wire technique or using the designed biodevice, to be in contact directly to a hand is required to obtain the high frequency component.

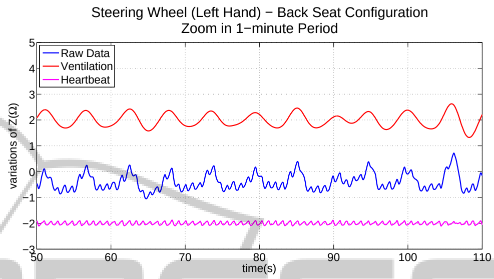

Figure 7: Zoom in to the figure 6 in a one-minute period. (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the cardiac rhythm.

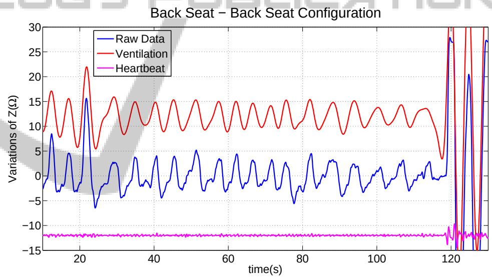

Figure 8: Back Seat - Back Seat Configuration using a 2-wire measurement technique. (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the cardiac rhythm.

4.3 Influence of the Thickness of Clothing

In the last group of measurements, dependencies on clothing are checked. Applying the same test explained above and the steering wheel - back seat configuration of electrodes, a subject is monitored wearing three different clothing. In figure 9, the signal is measured wearing a thin 100% cotton T-shirt. On the other hand, over this T-shirt a thin 100% polyester jacket and a thick sweater are worn in figures 10 and 11, respectively.

Note that the respiration rate is different in the three figures. In figures 10 and 11, the respiration rate is around 8 breaths per minute, lower than the minimum respiration rate for normal condition in adults. On the other hand, in figure 9 a normal rate of 11 breaths per minute can be observed. Furthermore, as thicker the clothing, the measured signal is less similar to the reference ventilation signal, refered to the thoracic band.

Therefore, there seems to be a correlation between clothing and the measured signal. Depending on the clothings, the biodevice could not work properly because of some inhalations or exhalations cannot be monitored. In fact, due to the capacitive behavior of the textrodes, this problem could be solved using an injection signal with a higher frequency.

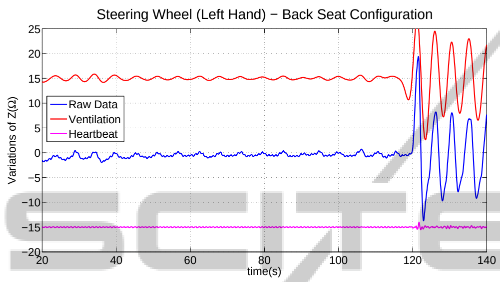

Figure 9: Steering Wheel - Back Seat Configuration with the driving electrodes in the left hand and in the right side of the back, respectively. The subject is wearing a thin T-shirt made of cotton (100%). (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the cardiac rhythm.

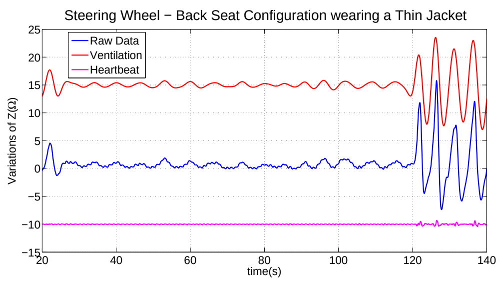

Figure 10: Steering Wheel - Back Seat Configuration with the driving electrodes in the left hand and in the right side of the back, respectively. The subject is wearing a thin jacket made of polyester (100%) over a thin T-shirt made of cotton (100%). (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the cardiac rhythm.

5 CONCLUSIONS

As shown in this paper, using a bioimpedance device, signals related to physiological parameters can be monitored. In this particular case, not only signals related to the ventilation are measured but also signals related to the cardiac rhythm. However, due to the fact that the use of standard metal electrodes are not recommended, new challenges related to the textile electrodes arise. Thus, to analyze the behavior

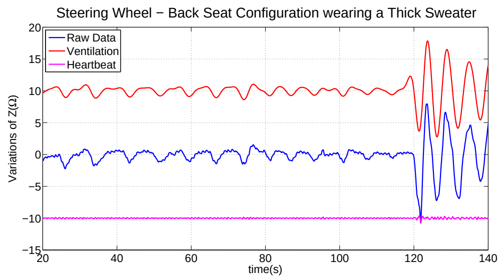

Figure 11: Steering Wheel - Back Seat Configuration with the driving electrodes in the left hand and in the right side of the back, respectively. The subject is wearing a thick sweater made of woolen (33%), polyester (27%), acrylic (27%) and polyurethane (13%) over a thin T-shirt made of cotton (100%). (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the cardiac rhythm.

of the clothing-textrode interface in depth is required. Furthermore, to test the bioimpedance device in a real environment is also required.

But, in any case, the tests in a simulation environment show a proper operation of the biodevice. This system is capable of monitoring the ventilation signal just like a thoracic band. Furthermore, the biodevice is also able to acquire the signal related to the cardiac rhythm. Therefore, this biodevice seems to be a further step to obtain a non-annoying non-invasive biodevice capable of monitoring some physiological parameters in a vehicle environment.

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