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Cardio-Respiratory and Daily Activity Monitor Based on FMCW Doppler Radar Embedded in a Wheelchair

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Abstract — **Unobtrusive monitoring of the cardio-respiratory and daily activity for wheelchair users became nowadays an important challenge, considering population aging phenomena and the increasing of the elderly with chronic diseases that affect their motion capabilities. This work reports the utilization of FMCW (frequency modulated continuous wave) Doppler radar sensors embedded in a manual wheelchair to measure the cardiac and respiratory activities and the physical activity of the wheelchair user. Another radar sensor is included in the system in order to quantify the motor activity through the wheelchair traveled distance, when the user performs the manual operation of the wheelchair. A conditioning circuit including active filters and a microcontroller based primary processing module was designed and implemented to deliver the information through Bluetooth communication protocol to an Android OS tablet computer. The main capabilities of the software developed using Android SDK and Java were the signal processing of Doppler radar measurement channel signals, graphical user interface, data storage and Wi-Fi data synchronization with remote physiological and physical activity database.**

Keywords: unobtrusive monitoring, wheelchair user, FMCW Doppler radar, Android OS tablet computer

I. INTRODUCTION

Around the world, daily variations in ambient air pollution have been consistently associated with variations in daily mortality, cardiopulmonary and cardiovascular morbidity [1-3]. Breathing activity can be independently measured by common hardware, e.g., using a thoracic belt or a nasal thermistor, or through signal processing of electrocardiogram (ECG) [4] and heart rate variability series [5-6]. As fundamental problems, these methods seem to interfere with normal respiration, many subjects seem to modify their respiratory pattern unconsciously, once they become aware their respiration is monitored [5]. Therefore, unobtrusive monitoring of cardiorespiratory and cardiovascular signal will define the future in the field of public health, environmental management and prevention of diseases.

Furthermore, demographic developments, social changes, and the rising costs of health and social care (considering elderly population, people with chronic diseases and less mobility) increase the need for research programs that develop smart systems for vital signs and physical activity monitoring [6-9].

Regarding the physical activity the literature reports the usage of accelerometers for motor activity estimation [10]. Accelerometer based motor activity monitors assure good reliability and reproducibility of the data. However to obtain the user's motion when the wheelchair is stopped it is necessary to attach the accelerometer, the data acquisition device and the communication module on the wheelchair user's clothes that means the looseness of the unobtrusively of the system. Using exclusively the microwave Doppler radar embedded on the wheelchair an unobtrusive measurement of cardio respiratory and also the physical activity can be done in unobtrusive way.

In this paper is presented a smart wheelchair architecture characterized by the multi-use of FMCW Doppler radar sensors in order to extract data of the cardio-respiratory function, and motor activities associated with body motion in an immobile wheelchair or during manually operation of the wheelchair. One of the Doppler radar was used to measure the wheelchair traveled distance.

II. SYSTEM DESCRIPTION –HARDWARE

The system includes a sensing part expressed by a set of two microwave Doppler radar sensors (DRS1, DRS2), signal conditioning circuitry, and a data acquisition and communication module (Fig.1). The Doppler radar sensors are placed at the following locations: DRS1 is fixed in plastic base mounted 5 to 15 cm behind the backrest of the wheelchair and 35 cm over the wheelchair seat; DRS2 is fixed on a plastic base parallel to one of the wheels, 25 cm apart from the wheel center.

After signal acquisition and data coding by the acquisition and communication module (ACM), the data is transmitted through Bluetooth communication to the tablet computer that runs Android OS and performs the data storage in a local database and assures graphical user interface functionalities. The cardio-respiratory and

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physical activities information stored in the tablet computer database is synchronized from time to time with the Web based healthcare information system database.

Fig. 1. System architecture based on a smart wheelchair (CC – conditioning circuit, DRS1, DRS2 - Doppler radar sensors, ACM – acquisition and communication module, TB-tablet computer).

A. Microwave Doppler radar sensor

A Frequency Modulated Continuous Doppler radar sensor (DRS1) (see Fig.1) was embedded in the wheelchair to perform the non contact measurement of chest motion caused by the respiratory and cardiac activity. The usage of FMCW Doppler radar assures accurate measurement of the target motion but also the range, which can be useful to extract the wheelchair user posture during physical activity. The information about respiration and cardiac activity is obtained by analog and digital signal processing of DRS1 output signals. Considering the requirement of detecting small amplitudes of cardiac and respiration motions ($x_{cardiac}$ <0.15 mm and x_{resp}<2mm), and to minimize the size of the used Doppler radar device including the antenna, a 24GHz IVS-162 DRS was considered (Fig. 2). As the main characteristics of the used FSK/FMCW Doppler radar sensor are considered the use of two antennas: TX antenna (TX ant), that is associated to body incident microwave signal; and a RX antenna (RX ant) associated with microwave signal reflected by the body. The received signal is applied to the input of two mixers (M1 and M2) to extract the information about the motion direction that can be obtained by measuring the phase difference between the in-phase signal (I) and quadrature signal (Q). Acquiring I and Q and calculating the phase difference the direction of the body motion is obtained, which can be useful to estimate the posture and physical activity of the user of the wheelchair.

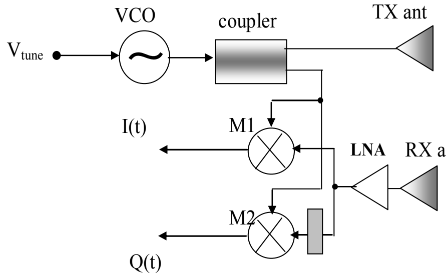


Fig. 2. FSK/FMCW Doppler radar sensor block diagram: M1, M2- mixers, TX, RX- transmit and receive antenna, VCO – voltage controlled oscillator, LNA-low noise amplifier.

According with Choi et al [11], the cardiac small motions, which correspond to blood pumping on the vessels, and the respiration motion that modulate the reflected RF signal is acquired by the RX ant:

$$V_{RX}(t) = A_{VRX} \cdot \mathrm{Re}\left(e^{j2\cdot\pi\cdot f_0\cdot t+\Phi(t)}\right) \qquad (1)$$

where A_{VRX} represents the amplitude of the reflected wave and $\Phi(t)$ represents the time varying phase caused by the periodic displacement due to breathing and cardiac activity through ballistocardiography. In this case, $\Phi(t)$ can be expressed by:

$$\Phi(t) = 2\pi\cdot\frac{2\cdot d(t)}{\lambda_0} = 2\pi\cdot\frac{2}{\lambda_0}\left(n\cdot\lambda_0 + x_{resp}(t) + x_{BCG}(t)\right) \quad (2)$$

where λ_0 is the wavelength associated with Doppler radar wave, λ_0=12,5mm for 24GHz. Since the change of the respiration and cardiac motion amplitudes (less than 2mm) are small compared with wavelength, the demodulated signal, $V_{RX}(t)$, is proportional to the respiration and cardiac motion ($x_{resp}(t)$, $x_{BCG}(t)$)[5].

$$V_{RX}(t) = A_{VRX}\cdot\left(\frac{4\cdot\pi\cdot\left(x_{resp}(t)+x_{BCG}(t)\right)}{\lambda_0}\right)$$

(3)

Thus, in the particular case of small periodic signals, such as respiration and cardiac motion (ballistocardiography) small changes of phase are obtained.

The frequency band of 24GHz (which is reserved internationally for industrial-scientific-medical purposes) was considered for microwave Doppler radar because assures better resolution of low amplitude motion through wheelchair backrest (polyester material) and wheelchair user's cloths, comparing with 2.4GHz and 10.5GHz which were used for vital signs monitoring, as reported in literature [12]. Also, this high frequency band is more appropriate for developing compact sensor with small size of the antenna. However, the solution presents a reduced range that it is not critical considering that DRS1 and DRS2 are located at 5-15 cm from the target. Regarding wheelchair user's cloths, materials such as 100% cotton, 100% polyester and even E-textile were tested with good results concerning the vital signs extraction when the radar sensor is used.

B. Conditioning, Acquisition and Wireless Communication

According to the theory, the respiration, $x_{resp}(t)$, and radar ballistocardiography signal, $x_{BCG}(t)$, are part of the received $V_{RX}(t)$ signal delivered by the DRS1, through I1 output. Thus, a 2nd order active low pass filter, characterized by a cutoff frequency f_c=0.3Hz was designed and implemented to extract the $x_{resp}(t)$ component of the $V_{RX}(t)$. On the other hand, a 2nd order active high pass filter was designed and implemented to extract the $x_{BCG}(t)$ component of the $V_{RX}(t)$. Additionally, two programmable gain amplifiers (PGA1 and PGA2) based on INA122 and CD4051 were implemented to assure the appropriate gain according to analog input range of the acquisition and communication module (BlueSentry architecture type).

Regarding the physical activity of wheelchair user, DRS1 and DRS2 Doppler radar devices were used to sense both wheelchair motion, manually operated (DRS2), and also to detect the wheelchair user's motion, using DRS1, while he can perform different activities related with the motion of different parts of the body when the wheelchair is not in motion or when a health care accompanying person assures the motion of the wheelchair.

The motion of the wheelchair manually operated by the user or by an accompanying person is sensed using the DRS2. V_{I2} and V_{Q2} output signals (M1, M2 outputs, see Fig.2) are filtered by two channel active high pass filter HPF2 (1st order fc=0.3Hz), amplified in the two channel amplification scheme (A3) based on INA122 instrumentation amplifier, and applied to the analog input of the acquisition and Bluetooth data communication module (ACM).

The block diagram of the implemented conditioning, acquisition and data communication module is presented in Fig. 3.

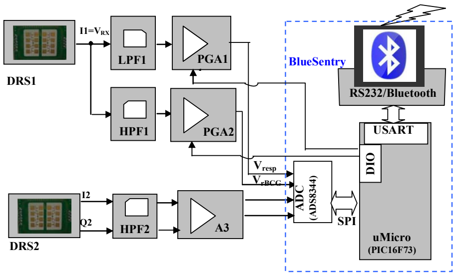


Fig. 3. Signal conditioning, acquisition block and wireless communication block diagram (HPF1, HPF2 – high pass filters, PGA1, PGA2 – programmable gain amplifier, A3 – instrumentation amplifier, Bluesentry - acquisition and data communication module)

The ACM performs an analog to digital conversion using a 16bit ADC (ADS8344) that communicates through the SPI bus with a 16F673 PIC microcontroller. The digital values of the acquired samples are delivered in hexadecimal form to the tablet computer that assures the digital codes to normalized voltage conversion: dresp→Vn_{resp}, d_{rBCG}→Vn_{rBCG}. The processing of the Vn_{resp} and Vn_{rBCG} associated with DRS1 measurement channel, is done at the tablet level in order to extract information on respiration rate, heart rate and the activity index (based on the evolution of the V_{RX} signal variance during changes in amplitude movements). The signals acquired from the DRS2 channels are also processed to extract the informations about the distance and the average velocity associated with the wheelchair motion.

III. SYSTEM DESCRIPTION - SOFTWARE

The main component of the "smart wheelchair" software is the tablet computer embedded software implemented to assure the intermediate processing of the data, human computing interfacing and data communication with the ACM and also with the Web based information system that hosts a physiological parameters database.

A Toshiba tablet computer running the Android 2.2 mobile OS was used. Using Android SDK and the Java programming language under Eclipse, the communication, data processing and representation on the tablet display as well as the data management are done. Important elements of the embedded software are the Activity Classes that are mainly related to the implementation of the user computing interfacing. In the present prototype were implemented a set of activity classes: *Sync.java* that permits to manage all the informations regarding the application; *DashBoard.java* that assures the numerical and graphical representation of physiological information (respiration and cardiac activity) but also elements associated with physical activity (wheelchair traveled distance, wheelchair velocity, user activity index). A peak detection procedure was implemented to calculate the heart rate and breathing rate. The activity index i_a, calculation was done considering counts per minute and standard deviation of detected movement amplitude that overcome an imposed threshold (e.g. th_{active}=0.05).

IV. RESULTS AND DISCUSSIONS

Using a LabVIEW software running in a laptop PC, the testing and validation of the whole system including the radars and the ACM was carried out. In order to highlight the capability of the implemented microwave radar based measurement system to assess the cardiac, respiratory and physical activity, tests were performed on 8 male healthy volunteers (height between 168 -182 cm, mean 179 cm; body mass index between 24-33).

As reference system for cardiac activity monitoring was used the ECG P-OX 100 system, the analog output of this instrument being acquired simultaneously with the signal obtained on the output of the PGA2, rBCG(t). In Fig. 4 and Fig. 5 it can be observed the coincidence of R wave of ECG signal with the main peaks of the rBCG signals unconcerned with trunk orientation, which underlines the capability of the method to provide accurate results on heart rate monitoring. Low difference between the two methods for measuring heart rate was observed - the mean difference was -1.12 and 95% confidence interval of the difference was -7.07/+ 4.83. No significant differences were observed when subjects wear cotton T shirt, polyester T shirt or E-textile.

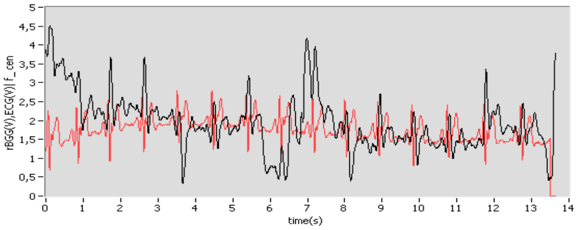


Fig. 4. Example of the rBCG and ECG signals recorded for a healthy wheelchair user with parallel orientation of the user's body trunk with the wheelchair backrest

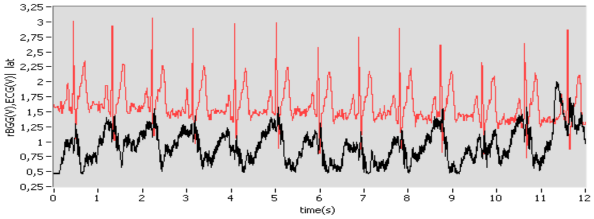
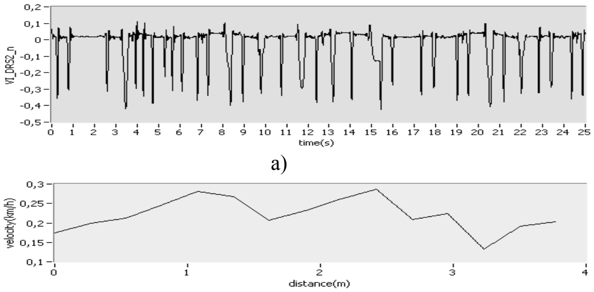


Fig. 5. Example of the recorded rBCG and ECG signals for a healthy wheelchair user with angular orientation of the user's trunk reported to the wheelchair backrest plan

At the same time it can be observed the existence of the artifacts associated with the small motion of the volunteer seated on the wheelchair that can be removed improving the order of the implemented high pass filter.

Although for high amplitude of wheelchair's user motion, cardiorespiratory signals are not possible to be obtained, information on user state can be extracted through DRS1 measurement channel.

The signals obtained from DRS2 related with wheelchair travel distance and velocity are presented in Fig. 6.

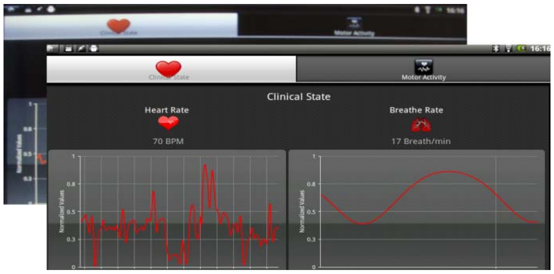


a)

b)

Fig. 6 Example of the recorded motion signal velocity measured through the DRS2 usage during manually operation by the user: a) The evolution of the normalized voltage signal acquired from DRS2 measuring channel , b) The evolution of wheelchair' calculated velocity

The graphical user interface, (fig.7), implemented on the Tablet computer level assures the ballistocardiography and respiration waves visualization, as well as, the values of the heart rate and respiration.



Heart Rate
70 BPM

Breathe Rate
17 Breath/min

Fig. 7. The developed cardiac, respiratory and motor activity graphical interface implemented on the Android OS Tablet computer

Motor activity index, as so as the distance and velocity of manually operated wheelchair, were also graphically represented in the implemented graphical interface.

V. CONCLUSION

This work evaluates the use of 24GHz FMCW Doppler radar to perform multi-function sensing as part of pervasive healthcare system. Appropriate conditioning circuit, data acquisition and wireless communication module are designed and implemented in order to assure the control and analog signal processing of the signals associated with FMCW Doppler radar. The acquired signals are transmitted to an Android OS Tablet computer that performs the digital signal processing to extract information on heart, respiration rate but and also to quantify the physical activity of the wheelchair user.

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