System for Validation of Doppler Radar Sensors for Heartbeat and Respiration Monitoring

Vladimir Petrović, Nebojša Malešević, Milica Janković, Bojana Petrović and Veljko Mihajlović

Abstract— **Non-contact detection of heartbeat and breathing rate has great potential for various applications (health systems, sleep studies, rescue, motion detection/correction etc.). One of the most promising ways for non-contact physiological measurement is using Doppler radar technology. This paper presents the design of the system for evaluation of Doppler radar sensor capabilities used for detection of heartbeat and respiration rate. Developed environment consists of: 1) radar sensor data acquisition board, 2) software for data acquisition and logging and 3) mechanical emulator which simulates human's movements due to breathing and cardiac activity in normal physiological range. Finally, we used the designed environment to test the custom-made Doppler radar sensor.**

Index Terms—**heartbeat, respiration, Doppler radar, emulator.**

I. INTRODUCTION

CARDIOPULMONARY monitoring is usually done by contact sensors such as electrocardiogram (ECG) electrodes for heart activity observation or different types of transducers for direct and indirect measurement of respiratory efforts (spirometers, pulse oximeters, plethysmographs, strain gauge systems for measuring of thoracic circumference etc.) [1]. However, the usage of contact sensors has serious drawbacks like skin damage, limited mobility and discomfort. The development of communication technologies has allowed wider and more reliable use of non-contact sensors. Non-contact detection of heartbeat and breathing rate has great potential for application in systems for sleep studies [2], hospital and home health monitoring [3], [4], searching for victims (in the ruins, under the snow, etc.) [5], for motion correction in medical imaging and radiotherapy systems [6]. One of the most promising ways for non-contact physiological measurement is using Doppler radar technology [7], [8]. Those systems enable continuous and remote physiological monitoring, through clothes or other obstacles, and independently and simultaneous following of heart and respiration signals as well.

The development of the radar-based device for the measurement of the cardiopulmonary signals requires relevant human emulator for the tuning of the signal processing parameters. There are commercially available patient simulators for training of medical staff in routine patient care but also in critical emergencies. Those simulators are usually expensive and include a lot of options that are necessary for medical intervention but are useless in testing Doppler radar sensors for heartbeat and respiration rate detection. In order to provide emulator for the testing and developing of algorithms for cardiopulmonary monitoring, we designed and manufactured a low-cost system that includes the mechanical emulator of human thorax. We presented design considerations and description of the hardware and software platform for validation of Doppler radar sensors for heartbeat and respiration rate measurements in the Section II. Results of testing of a commercially available Doppler radar sensor by developed system are described in Section III. Finally, we gave conclusion and plans for future work in the Section IV.

II. THE METHOD

A. Design considerations

The requirements for the mechanical model include respiration and heart activity simulation in the manner that takes into account the range of physiologically valid values for adults [9], [10], [11]:

- normal heartbeat rate range 1-1.67 Hz (60-100 min^{-1})
- peak-to-peak motion due to heartbeat 0.2-0.5 mm
- normal respiration rate range 0.2-0.33 Hz (12-20 min^{-1})
- peak-to-peak chest motion due to respiration 4-12 mm.

Block scheme of the designed system for characterization of Doppler radar sensors for heartbeat and respiration monitoring is presented in Fig. 1.

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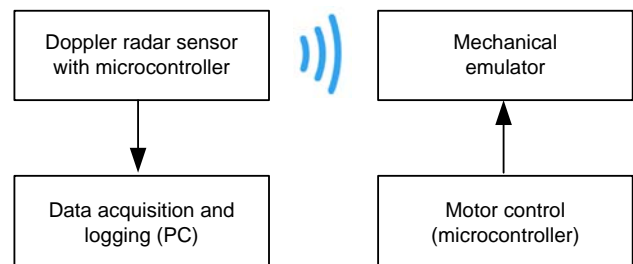
Fig. 1. Block scheme of the system for characterization of Doppler radar sensors for heartbeat and respiration monitoring

The system includes: 1) mechanical emulator which simulates breathing and heartbeat movements with the microcontroller for motor control, 2) Doppler radar sensor with microcontroller which acquires the radar data and sends it to the PC via serial interface, and 3) software for data acquisition and logging.

B. Mechanical emulator and motor control

The mechanical emulator needs to simulate breathing movements of human thorax and much smaller movements of skin due to the heartbeat. Emulation of these movements needs to be separately controlled in order to realize wide range of respiration rate and heartbeat range.

Fig. 2 shows the diagram of the proposed mechanical emulator. It consists of: 1) stable stand with a motor that controls breathing emulation inside, 2) vertical moving stick that mimics the movement of human thorax due to breathing, 3) another motor for controlling the emulation of heartbeat that is fixed to the moving stick, 4) round elastic rubber that emulates human skin and is fixed to the rubber frame. We used servomotors because they are easily controllable and provide enough torque and speed for our application. For emulation of breathing movements, we used Hitec HS-422 servomotor [12] and for emulation of heartbeat movements, we used Hitec HS-311 servomotor [13].

Moving part bar lies on the servomotor horn and moves up and down as the horn rotates. Initial position of the servomotor according to the notation from Fig. 2 is set to $\theta = 0°$. In order to provide vertical movement of Δh_b, the servo needs to rotate for

$$\theta = \arctan\frac{\Delta h_b}{r_b}, \qquad (1)$$

where $r_b = 2$ cm is the distance from moving stick and servomotor axle in the initial position. For physiological range of movements 4-12 mm, the needed angle range is 11.3°-31°. The minimum step of both servomotors of 0.45° provides us the possible breathing emulation movement range of 44 steps.

Heartbeat movements are emulated by pushing the elastic rubber for 0.2-1 mm. As we show in Fig. 2, the servomotor horn pushes the rubber for Δh_h when rotates from angle position θ_1 to the angle position θ_2. In order to provide the movement of Δh_h, the servo for heartbeat emulation needs to rotate to

$$\theta_2 = \arcsin\left(\frac{\Delta h_h}{r_h} + \sin(\theta_1)\right), \qquad (2)$$

where $r_h = 2.5$ cm is the length of the servomotor horn. In our system θ_1 was set to 45°. Using the (2) we calculated the needed range of θ_2 which is 45.65°-48.34°. This range is crossed in 6 steps. The resolution can be increased by setting the initial angle position to a larger value, e.g. 50° or 55°. The

angle θ_1 can be adjusted by changing the heartbeat emulation servomotor's vertical position. However, in that case the change of pushing point position is larger, hence we decided to leave θ_1 at 45°.
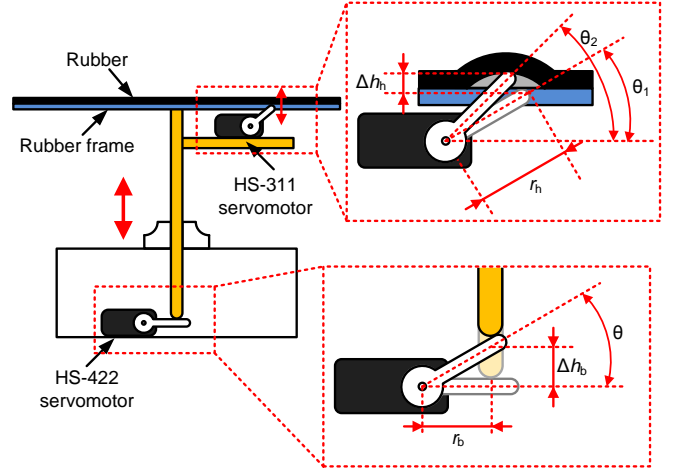
Fig. 2. Diagram of the mechanichal emulator. Enlarged parts represent servomotors for breathing and heartbeat emulation in two possible positions.

Servomotors are controlled using two independent Arduino UNO boards [14]. We used Arduino's Servo library which we modified to achieve the full range of 400 steps. The code calculates the needed angles and incrementally changes the position with the delay that is determined by the frequency of the emulated heartbeat and breathing.

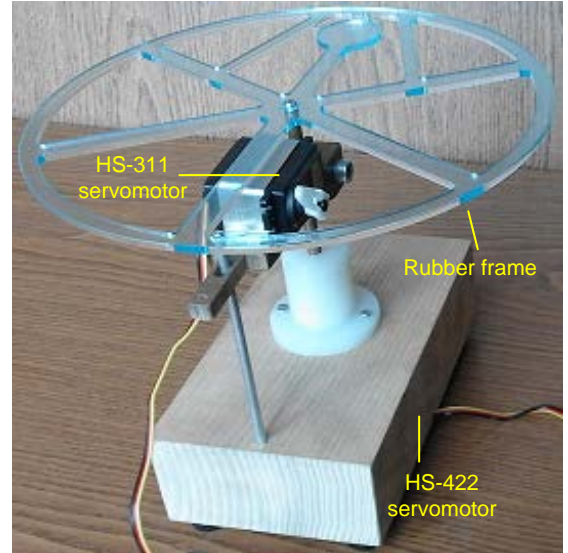The photography of the designed mechanical emulator is shown in Fig. 3.

Fig. 3. Mechanical emulator - physical model

C. Data acquisition and logging

We used our mechanical emulator for validation of RM024ARF2 Doppler radar system (antenna frequency range 24 GHz, radio frequency range 3 kHz-300 GHz, demonstrator

prototype made by NovelIC L.L.C., Belgrade, Serbia). A custom-made board is used for data acquisition and sending to the PC. The board contains microcontroller which samples the radar data ($f_S = 1$ kHz) and sends it via UART serial interface to the PC.

We developed the PC application in Python ver. 3.6 which communicates with the acquisition board. The graphical user interface (GUI) of the application is shown in Fig. 4. PyQt library was used for GUI development. This application enables:

- data acquisition setting (COM port, sample frequency, import/export configuration file)
- real-time plotting of data from Doppler radar system
- data manipulation (zooming, edit axes or curve parameters and saving current graph image to the image, pdf or post script file)
- logging data into ".txt" file for offline processing (simultaneously with the real-time monitoring).
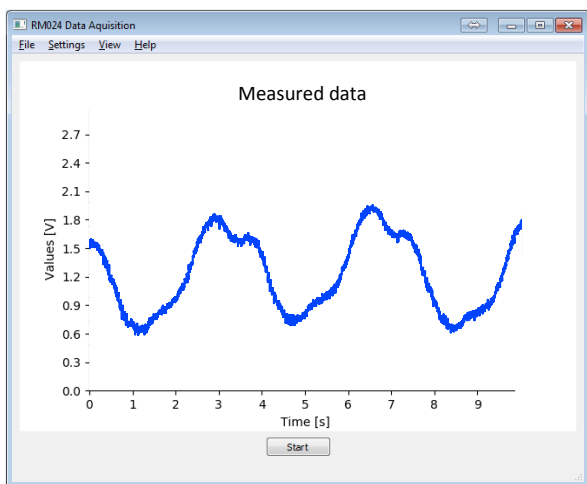

Fig. 4. Graphical user interface for data acquisition and logging from Doppler radar system

D. Offline data processing

Acquired data from radar system correlates to the distance between rubber and radar system. After acquisition, additional analysis was performed offline. Firstly, the DC component of the signal was removed. After that, the resulting signal was averaged using the low pass FIR filter. In the end, the Fourier analysis of the filtered signal was performed.

III. RESULTS

A. Measurements of vital signs in a human subject

The spectrum of signals acquired using radar sensors for vital signs usually includes: harmonics that come from breathing movement and harmonics that come from much less intensive heartbeat movements [8]. In order to approve that RM024ARF2 sensor is able to detect such signals, we made an experiment in which vital signs in a human subject were monitored. The experimental setup is shown in Fig. 5. The radar sensor is placed in front of the human subject and data were acquired while the person is steadily breathing. For

validation, the heartbeat rate was also measured using the pulse oximeter PULOX PO-200 [15] and respiration rate was estimated by visual inspection and counting breaths.
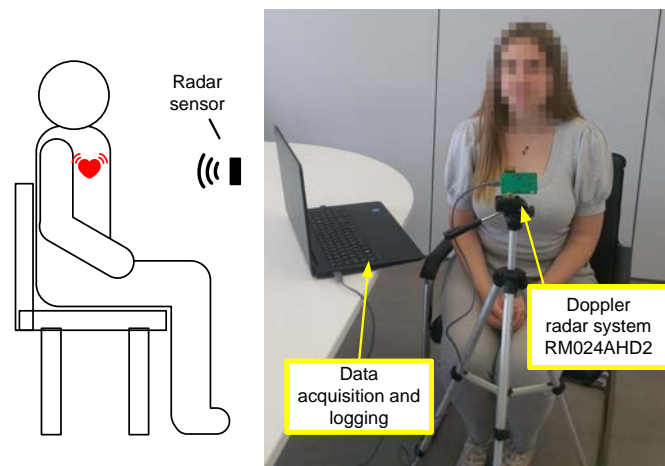

Fig. 5. Experiment setup for measuring vital signs on humans, a scetch (left) and photography of the experiment (right).

One of the acquired signals and its spectrum are shown in Fig. 6. The experiment approved the statement from [8], as can be seen from Fig. 6.b) in which we marked the harmonics that come from breathing movement and harmonics that come from heartbeat movements.

It is important to mention that the periodicity of the signal is very sensitive to random body movements other than movements which come from breathing and heartbeat.
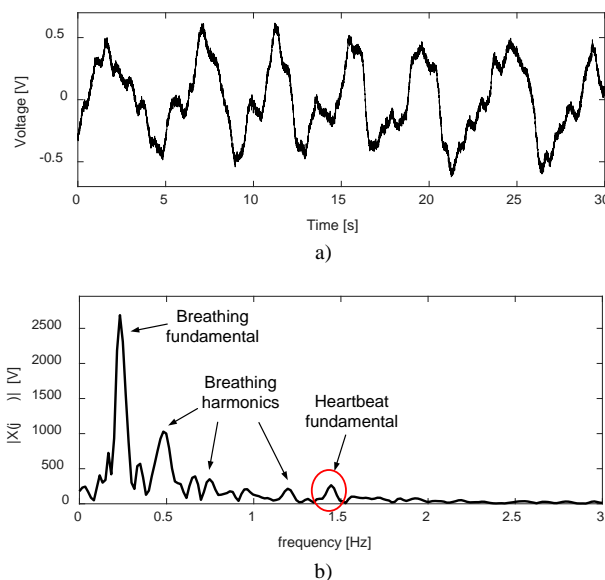

Fig. 6. Measurements in human subject: acquired signal from radar system a) and its spectrum b). Breathing rate was 0.25 Hz (15 min^{-1}), while the average hearbeat frequency was 1.45 Hz (87 beats/min^{-1}).

B. Experiments on the designed emulator

In order to approve our emulation system we made experiments with different heartbeat and breathing emulation frequencies and amplitudes of movement. The experimental

setup is shown in Fig. 7. The radar sensor is placed above the mechanical emulator in order to measure distance which is changed due to breathing and heartbeat emulation movements. The acquired data is logged to the PC where the signals are further offline processed.
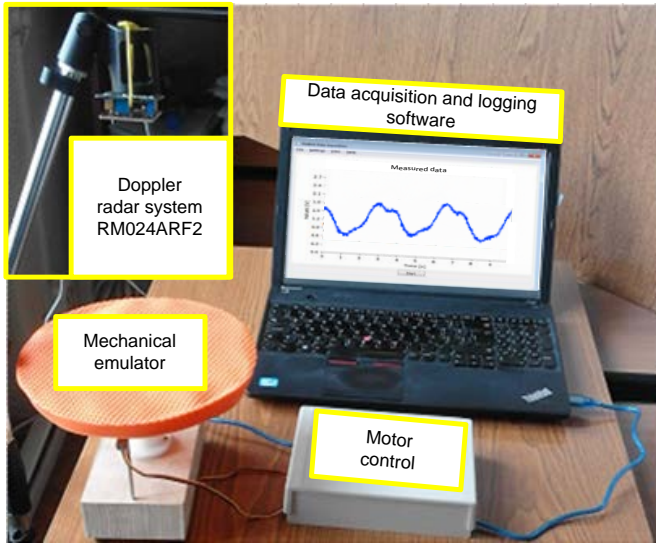

Fig. 7. Experiment setup for emulator validation

Firstly, we tested the breathing emulation and heartbeat emulation separately in order to identify the time shape of the signals. After that we turned on the emulation of both the breathing and the heartbeat. The acquired signals are shown in Fig. 8.
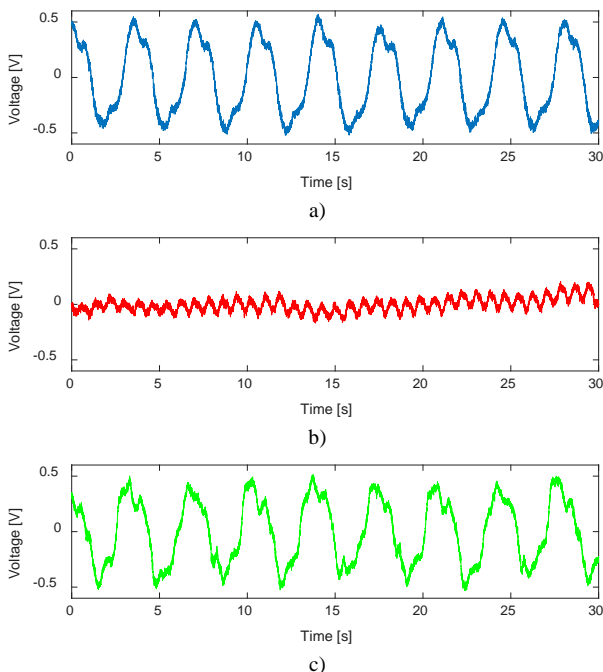

Fig. 8. Acquired signals from radar system for: a) only breathing emulation, b) only heartbeat emulation and c) both the breathing and the heartbeat emulation turned on. Breathing parameters were 0.28 Hz (17 min^{-1}), movement amplitude 5 mm. Heart parameters was set to 1.25 Hz (75 min^{-1}), movement amplitude 0.5 mm.

Spectrums of acquired signals from radar system are shown in Fig. 9. Note the circled peak in the spectrum of signal acquired for both the breathing and the heartbeat emulation (Fig. 9.c)) that represents the heartbeat emulation. We noticed that it cannot always be seen, especially when the heart-beat movement is small. Even when the movement is close to the upper bound of the heartbeat movement range, it can be concealed by the harmonic of the signal that comes from breathing emulation. This is the property of the radar sensor which obviously cannot always detect both movements, but opens possibilities for further digital signal processing algorithms which can improve sensor capabilities.
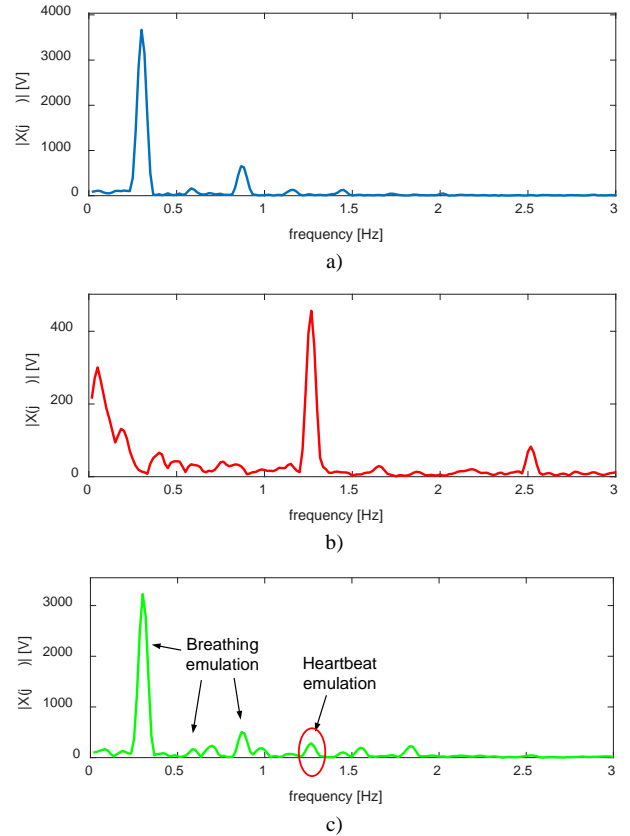

Fig. 9. Amplitude spectrums of signals from Fig. 8. a) only breathing emulation, b) only heartbeat emulation and c) both the breathing and the heartbeat emulation turned on.

IV. CONCLUSION

In this paper we presented the system for evaluation of Doppler radar sensors used in biomedical applications. We focused our design on vital signs emulation, particularly the breathing and the heartbeat. The system is capable to emulate breathing and heartbeat rates inside normal physiological range. Also, it is adjustable to any chest motion inside the normal physiological range.

We presented the experimental setup using our system for validation of RM024ARF2 Doppler radar sensor. The tested sensor was capable to detect signals that come from breathing and heartbeat movement emulation but not for all combinations of emulated heart and breathing rate and amplitudes of emulated movements. This is why we plan to

further improve signal processing algorithms for breathing and heartbeat rate detection from the acquired signals. This is where the designed mechanical emulator will indubitably have its role before testing algorithms on humans and in real situations.

REFERENCES

[1] J. Webster, *Medical instrumentation: application and design*, *4*th ed. New York, USA: John Wiley & Sons, 2009.

[2] M. Kagawa, K. Ueki, H. Tojima, T. Matsui, "Noncontact screening system with two microwave radars for the diagnosis of sleep apnea-hypopnea syndrome," Proceedings on the 35th Annual International Conference of the IEEE, Engineering in Medicine and Biology Society (EMBC), Osaka, Japan, pp. 2052-2055, 3-7 July, 2013.

[3] Y. Chen, D. Misra, H. Wang, H. Chuang, and E. Postow, "An X-band microwave life-detection system," *IEEE Transactions on Biomedical Engineering*, vol. BME-33, no. 7, pp. 697–701, Jul. 1986.

[4] D. Obeid, G. Zaharia, S. Sadek, and G. El Zein, "Microwave Doppler Radar for Heartbeat Detection Vs Electrocardiogram," *Microwave and Optical Technology Letters*, vol. 54, no. 11, pp. 2610-2617, Aug. 2012.

[5] M. Bimpas, N. Paraskevopoulos, K. Nikellis, D. Economou, and N.K. Uzunoglu, "Development of a three band radar system for detecting trapped alive humans," *Progress In Electromagnetics Research*, vol. 49, pp. 161-188, 2004.

[6] C. Gu, R. Li, R. Fung, C. Torres, S. Jiang, C. Li, "Accurate respiration measurement using DC-coupled continuous-wave radar sensor for motion-adaptive cancer radiotherapy," *IEEE Trans Biomed Eng* vol. *59*, no. *11*, pp. 3117–3123, 2012.

[7] O. Boric-Lubecke, V. M. Lubecke, A. D. Droitcour, B. K. Park, and A. Singh, *Doppler Radar Physiological Sensing*. Hoboken, NJ, USA, John Wiley & Sons, 2015.

[8] C. Li, J. Cummings, J. Lam, E. Graves, and W. Wu, "Radar Remote Monitoring of Vital Signs," *IEEE Microwave Magazine*, vol. 10, no. 1, pp. 47–56, Feb. 2009.

[9] A. De Groote, M. Wantier, G. Cheron, M. Estenne, and M. Paiva, "Chest wall motion during tidal breathing," *Journal of Applied Physiology*, vol. 83, no. 5, pp. 1531-1537, Nov. 1997.

[10] G. Ramachandran and M. Singh, "Three-dimensional reconstruction of cardiac displacement patterns on the chest wall during the P, QRS, and T-segments of the ECG by laser speckle interferometry," *Medical and Biological Engineering and Computing,* vol. 27, no. 5, pp. 525-530, Sep. 1989.

[11] G. Shafiq, G. K.C. Veluvolu, "Surface Chest Motion Decomposition for Cardiovascular Monitoring," *Scientific Reports*, vol. 4, no. 5093, pp. 1-9, 2014.

[12] http://hitecrcd.com/products/servos/sport-servos/analog-sport-servos/hs-422-deluxe-standard-servo/product, last accessed May 2017.

[13] http://hitecrcd.com/products/servos/sport-servos/analog-sport-servos/hs-311-standard-economy-servo/product, last accessed May 2017.

[14] https://www.arduino.cc/en/main/arduinoBoardUno, last accessed May 2017.

[15] https://www.pulox.de/po-200-v_en, last accessed May 2017.