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Noncontact Heart Rate Measurement using a 24 GHz Doppler Radar

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***Abstract* — Current heart rate measurement methods include the use of ECG or pulse oximeter systems. While these systems are effective, they require skin contact. It has been demonstrated that Doppler radars can be used to measure heart rates too. This paper presents the design of a modified 24 GHz Doppler system. The modified signal conditioning board uses a 2-stage amplifier and a simple dc offset compensation circuit. The design removes the unstable problem and reduces circuit noise. The signal processing algorithm used is also presented. Measurements on 16 volunteers were made using the modified system and promising results have been obtained.**

***Index Terms* — Doppler radar, heart rate measurements, RF technology, remote monitoring, radar sensing.**

I. INTRODUCTION

The conventional way of monitoring cardiac activities is to use a surface electrocardiogram (ECG, EKG) to measure the heart's bioelectric variations. Noncontact measurement of cardiography using microwave technology was first reported by Lin, et al [1]. Advances in RF technologies have since enabled the development of small radar systems for use by such measurements. Indeed, several portable systems and IC's implemented with Doppler radars have been reported for remote heartbeat measurement [2] – [6]. Sensing frequencies used by these systems range from 1.6 GHz to 24 GHz, each having its own merits and limitations. In particular, the 24 GHz Doppler radar system described in [6] was developed by the authors of this paper. We adopted a fast prototyping approach for the design and development of the Doppler radar system. The design of the system takes into considerations the health safety regulations used in the various standards (e.g. FCC [7], IEEE [8], and ICNIRP [9]) too.

This paper presents further work done and results obtained on the Doppler radar system reported in [6]. Specifically, the design has been modified to enhance the stability as well as compactness of the radar system, without compromising the health safety requirements. This paper describes the modified hardware and heart rate estimation method. The performance of the modified system has been evaluated under different conditions and promising results have been obtained.

II. DESIGN OF THE MODIFIED DOPPLER RADAR SYSTEM

The block diagram of the design of the 24 GHz radar system developed by the authors is shown in Figure 1. Some photos of the system are shown in Figure 2.

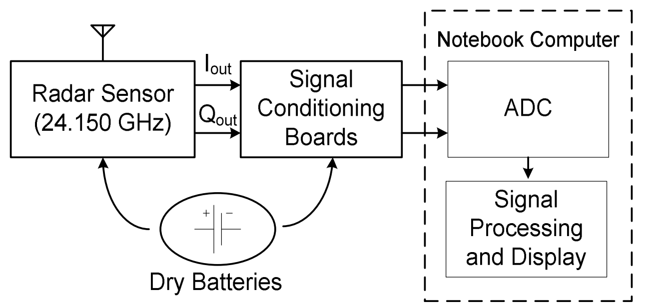

Fig. 1. Block diagram of the 24 GHz Doppler radar system design

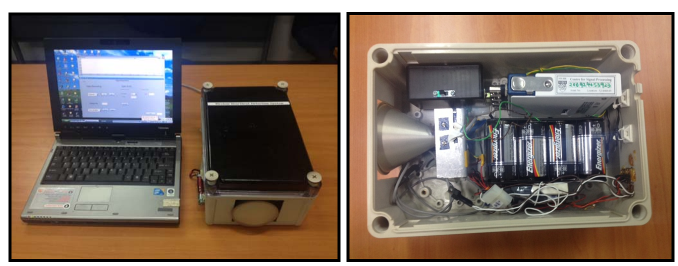

Fig. 2. Photos of the 24 GHz radar system (left: system, right: interior layout)

The radar sensor is an off-the-shelf Doppler sensor head, SRF-24120910-D1, which houses the transmitter and receiver RF circuits, and a directional antenna. The sensor transmits a continuous wave (CW) signal at 24.150 GHz with a power of 10 dBm. The output of the received reflected signals are down converted to I- and Q- channels, each of which is fed to a signal conditioning module. The signal conditioning module is designed by the authors and it comprises a filter, an amplifier, and a dc offset compensation circuit. DC offset occurs due to

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imperfect practical conditions (e.g. clutter reflections from the background) and is in general time-varying. The outputs of the signal conditioning module are digitized by an ADC board, NI DAQCard-USB-9162. The digitized data are then fed to the computer, through an USB port, where the heart rates are estimated and displayed. The design of the system is in compliance with the health safety regulations adopted by the FCC, IEEE standards and ICNIRP which has been discussed in some details in [6] and will not be repeated here.

The modified signal conditioning module uses a 2-stage amplifier design and a simple dc offset compensation circuit. The 2-stage amplifier design removes the unstable problem and reduces circuit noise. The overall gain is about 52 dB. The final baseband output delivers a peak-to-peak voltage of 1.6 V typically. The modified module used for the system is much smaller than the original design as can be seen in Figure 3.

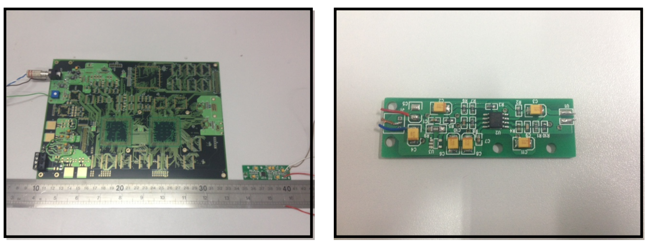

Fig. 3. Photos of the signal conditioning modules (left: large board is the module used in previous design while the small board is the module used in the modified design; right: enlarged photo of the module used in the modified design)

The heart rate is estimated by using the following digital signal processing algorithm.

After passing through the signal conditioning module, the filtered amplified I- and Q- signals are sampled by the ADC. Let the corresponding sampled signals be,

$$s_i(n) = A_i(n)\cos\left[p(n)+\theta\right] \qquad (1a)$$

$$s_q(n) = A_q(n)\sin\left[p(n)+\theta\right] \qquad (1b)$$

where n = 1, 2, …, A_i, A_q are the amplitudes of the sampled I- and Q- signals, $p(n)$ is the sampled chest wall displacement which is time-varying, and θ is a constant phase shift.

Dividing (1b) by (1a), and taking arctangent of the resultant expression, we have the demodulated phase,

$$\phi(n) = \arctan\left[\frac{s_q(n)}{s_i(n)} \cdot \frac{A_i}{A_q}\right] = p(n)+\theta \qquad (2)$$

where the amplitude imbalances A_i and A_q can be obtained from the calibration process.

A short-time Fourier transform (STFT) is next performed on N consecutive samples of the demodulated phase {□(n)}, n = 1, 2, …, N, to obtain the frequency spectrum of □(n). The resultant signal is then high-passed to obtain the frequency spectrum {$P(n)$} of {$p(n)$}, n = 1, 2, …, N.

As $p(t)$ describes the waveform of the chest wall movement, the corresponding heart rate can be estimated from {$P(n)$} using a peak detection algorithm. The same method allows us to estimate the respiratory rate too as $p(t)$ can be modeled as a sum of the chest wall movements induced by the heartbeat and the breathing action.

III. Experiments

The modified Doppler radar system was used to measure the heart rates of 16 human volunteers in the laboratory. The ages of these 16 test subjects range from about 25 to 40 years. A wired finger pressure pulse transducer (UFI 1010) was also used to measure the heart rates of the test subjects at the same time and used as the reference for accuracy computation.

During measurements, test subjects (with cloths) were asked to sit still and breathe normally for one minute. The test was repeated at different distances and off-axis angles.

IV. Results and Discussions

A sample of the demodulated waveform and spectrum of the received signals are shown in Figures 4 and 5 respectively.

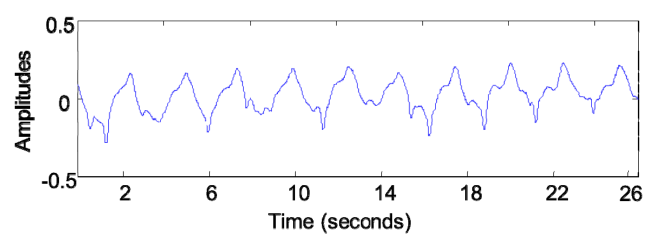

Fig. 4. Demodulated waveform of the received signal

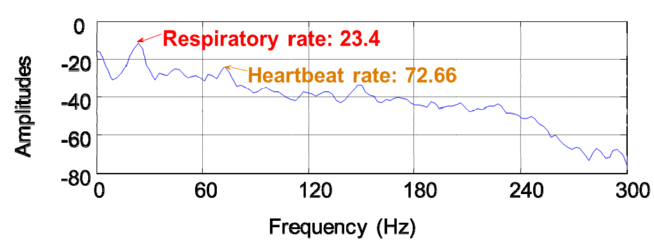

Fig. 5. Frequency spectrum of the processed reflected signals.

The average heart rates measured by our system (modified 24 GHz Doppler radar system) and the reference system (UFI 1010) for a distance of 0.5m are shown in Figure 6.

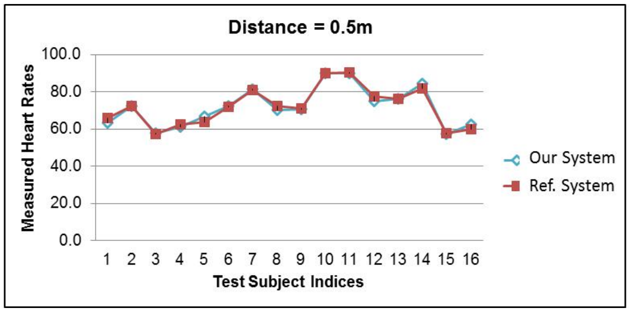

Fig.6. Measured heart rates of test subjects (distance = 0.5m)

It can be seen from Figure 6 that, the results obtained by our system is very similar to that measured by the referenced system. The absolute error of the measured heart rates for the data shown in Figure 6 is computed to be 1.2 which is about 1.7% of the value measured by the reference system (pulse transducer). The absolute error is defined as,

$$|e| = \frac{1}{M}\sum_{i=1}^{M}\left|H_{s,i} - H_{r,i}\right| \qquad (3)$$

where $H_{s,i}$ and $H_{r,i}$ are the average heart rates measured for the i^{th} test subject by our radar system and the referenced system respectively, and M is the number of test subjects.

The performance of the modified radar system at longer distances has also been evaluated and the results are shown in Table I. The reference system shown in Table I (and II) is the finger pressure pulse transducer (UFI 1010) described above.

TABLE I
AVERAGE HEART RATES AT DIFFERENT DISTANCES

Distance	Our System	Ref. System	Absolute Error
0.5m	71.9	71.9	1.2 (1.7%)
0.8m	68.8	71.0	4.5 (6.3%)
1.1m	66.4	71.5	7.5 (10.5%)

Table I shows that, the system developed is able to estimate the heart rates with accuracies higher than 90% for distance up to about 1m. For higher distances, longer integration time will be needed to achieve a similar performance, which is being investigated by the authors and will not be discussed here.

The robustness of the system developed against imperfect alignments in angles (off-axis measurement) has also been investigated and the results are summarized in Table II.

TABLE II
AVERAGE HEART RATES FOR OFF-AXIS MEASUREMENT (0.5M)

Angles	Our System	Ref. System	Absolute Error
0^o	71.9	71.9	1.2 (1.7%)
5^o	69.8	69.3	3.6 (5.2%)
10^o	68.6	69.4	5.4 (7.7%)

As it can be seen from Table II, the system developed is quite robust against misalignment in angles up to more than 10^o off-axis measurements.

V. CONCLUSIONS

This paper presents the design and performance of a 24GHz Doppler radar system. The system is designed to measure heart rates at a distance (i.e. without the need to have body contact). The modified signal conditioning module and digital signal processing method are described in the paper. 16 human subject volunteers participated in heart rate measurements using both the system developed and a wired finger pressure pulse transducer (UFI 1010), where the latter was used as the reference system. The absolute error of the measurements has been calculated to be 1.7%. The distance and angle (off-axis) tests also showed that the system developed is quite robust for use at distances up to 1m and off-axis angle more than 10^o.

ACKNOWLEDGEMENT

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REFERENCES

[1] J. C. Lin, J. Kiernicki, M. Kiernicki, and P. B. Wollschlaeger, "Microwave apexcardiography," *IEEE Trans. Microwave Theory & Tech.,* vol. 27, no. 6, pp. 618-620, June 1979.
[2] C. Li and J. Lin, "Recent advances in Doppler radar sensors for pervasive healthcare monitoring," *IEEE Asia Pacific Microwave Conference APMC*, pp. 283-290, December 2010.
[3] A. D. Droitcour, O. boric-Lubecke, V. Lubecke, J. Lin, and G. T. A. Kovac, "Range correlation and I/Q performance benefits in single-chip silicon Doppler radars for noncontact cardiopulmonary monitoring," *IEEE Trans. Microwave Theory & Tech.,* vol. 52, no. 3, pp. 838-848, March 2004.
[4] Y. Xiao, C. Li, and J. Lin, "A portable noncontact heartbeat and respiration monitoring system using 5-GHz radar," *IEEE Sensors J.,* vol. 7, no. 7, pp. 1042-1043, July 2007.
[5] D. Obeid, G. Issa, S. Sadek, G. Zaharia, and G. El-Zein, "Low power microwave systems for heartbeat rate detection at 2.4, 5.8, 10 and 16 GHz," *First International Symposium on Applied Sciences in Biomedical and Communication Technologies ISABEL,* pp. 1-5, October 2008.
[6] X. Guo, W Ser, and Marcus E. H. Ong, "Cardiac activity detection: a fast prototyping approach with health safety considerations," *IEEE-EMBS Conference on Biomedical Engineering and Sciences,* pp. 1014-1017, December 2012.
[7] FCC, "FCC policy on human exposure to radio frequency electromagnetic fields," *URL*: www.fcc.gov/oet/rfsafety/.
[8] IEEE, "IEEE standard for safety levels with respect to human exposure to radio-frequency electromagnetic field, 3 KHz to 300 GHz," *IEEE Std. C95.1-1999*, April 1999.
[9] ICNIRP, "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 200 GHz)," *Health Physics*, vol. 74, no. 4, pp. 494-522, April 1998.