Non-contact estimation of breathing parameters based on CW radar

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***Abstract*—The present paper addresses the problem of contactless respiration monitoring system realization based on continuous wave radar (CWR). The developed system is composed of two parts, hardware and software parts. In hardware part, the main purpose is to realize a CWR by using low cost components. The software part is dedicated to develop algorithms for drawing the breathing rhythm and estimating the respiration frequency. Firstly, the received signal is processed and its phase is exploited in the estimation of the respiratory rhythm. Secondly, the respiratory frequency is estimated based on either the periodogram method, the autocorrelation method or on the combination of both methods. Numerical simulation, together with an experimental study have shown the efficiency of the proposed solution in estimating the respiratory rhythm and frequency.**

***Index Terms*—Breathing rhythm, breathing frequency, CW radar, phase unwrapping, periodogram, autocorrelation.**

I. INTRODUCTION

The recent Covid-19 pandemic showed many limitations of the actual health monitoring systems. In fact, the worldwide rapid spread of the coronavirus showed the imperative need of new technologies in estimating vital signals such as respiratory rate and rhythm. Hence, Self and remote health monitoring systems are of great concern in order to limit the contact between patients and the medical staff. We have considered in this paper the problem of estimating the breathing rhythm and frequency. In order to measure these parameters, two technologies can be used, the first one is based on contact sensors and the second one uses non-contact sensors. In many cases, contact based methods can not be used as is the case for a Covid-19 patient or a burn victim. To minimise this contact, non-contact technologies are in development path [1].

In this sense, monitoring the respiratory rate using a continuous wave (CW) radar is of particular interest. The use of this radars for health purposes has several advantages. These include low power consumption, simple radio architecture [2], [3], privacy respect feature [4] and non-contact nature. In this perspective, several works exist in the literature, which use different methods for the estimation of the breathing frequency. Among these methods, we can mention: the one based on the Fourier transform [5], the time-frequency analysis [6] and those based on the autocorrelation method [5].

In this paper, the presented algorithms have been developed for respiratory rhythm estimation based mainly on phase unwrapping and filtering. As well as, breathing frequency estimation. For this purpose we used three methods. The first one is based on the periodogram, the second one is based on the autocorrelation and the third one is based on the combination of the two first methods.

The rest of this paper is organized as follows. Section II, presents the mathematical model of human breathing and CW radar signals. The proposed method for estimating breathing rhythm and frequency is presented in section III. Section IV discusses simulation and experimental results and Section V gives a conclusion of this work.

II. DATA MODEL AND PROBLEM FORMULATION

During breathing, muscle contraction generates changes in the volume of the thorax and creates pressure differences between the thorax and the external environment. The vibrations of the thorax and abdomen cause large displacements on the surface of the skin. This displacement can be modelled as a periodic motion with a fixed frequency f_r and amplitude R_P.

$$R(t) = R_P \cos(2\pi f_r t + \phi_0) \quad (1)$$

Where:
R_P: the range of motion of the thoracic cage.
f_r: breathing frequency.
ϕ_0: initial phase of periodic movement of the chest cage.

Our objective is the realisation of a system for breathing parameters measurement. This system is based on a continuous wave radar. The choice of this type of radar is due to its design simplicity and low cost. This radar contains a transmitter and a receiver. Transmitted and reflected signals can be modelled as follows:

- **Emitted signal:** The emitted signal is a periodic wave which has a central frequency of $24GHz$.

$$S_e(t) = A\cos(2\pi f_C t) \quad (2)$$

Where A is the signal amplitude and f_c is the signal frequency.

- **Received signal**
  When a person is located in the main lobe of the radar, the emitted signal will be reflected by the parts of his body which are illuminated by the radar and specifically in our case the thoracic cage. The movement of the chest and abdomen introduces a Doppler shift. Hence, the reflected signal is given in Eq. (3).

$$S_r(t) = \alpha A\cos(2\pi f_c(t - D(t)/c)) + w(t) \quad (3)$$

Where:
$S_r(t)$: Received signal at the input of the receiver.
α: Attenuation coefficient.
$w_(t)$: Propagation channel noise.
$D(t)$: Distance between receiver and subject which is given by:

$$D(t) = D_0 + R(t) \quad (4)$$

Where D_0 is the average distance between the subject and the receiver.

After reception, S_r signal is demodulated by a portion of the emitted one, and its $\frac{\pi}{2}$ shifted phase, which gives two components I and Q. These components are filtered by a low-pass filter with a cut-off frequency equals to the transmission frequency f_C. After filtering, components are amplified by a gain G. Mathematical expressions of I and Q are given in Eq. (5).

$$\begin{cases} I(t) = K\cos(-4\pi\frac{D(t)}{\lambda}) + w_1(t) \\ Q(t) = K\sin(-4\pi\frac{D(t)}{\lambda}) + w_2(t) \end{cases} \quad (5)$$

Where $K = \frac{G\alpha A}{2}$ and $w_i(t)$ is an additive noise.

III. PROPOSED METHOD

The estimation of respiratory parameters is mainly divided into two parts. First, the respiratory rhythm $R(t)$ is estimated, which is done in three steps: the first one is the estimation of the phase of the complex version of the received signal $I + jQ$. Phase unwrapping is done in the second step, followed by filtering as a third step. In the Second part of the estimation of respiratory parameters, we consider the estimation of the respiratory rate f_r. For this purpose, three methods have been developed. The first method is based on the periodogram, the second is based on the autocorrelation and the third is based on the combination of both the autocorrelation and the periodogram. The processing algorithm for breathing parameters estimation is summarised in Table I.

IV. RESULTS AND DISCUSSION

Performance and results of the developed algorithms are evaluated by numerical simulations and validated with experimental data.

TABLE I
ALGORITHM FOR ESTIMATING BREATHING RHYTHM AND BREATHING FREQUENCY

Inputs: $S = I + jQ$.
Estimate the breathing rhythm R_p
Estimate the phase ϕ of the complex signal S.
Unwrap the phase ϕ.
Filter the unwrapped phase by a FIR filter.
Filter with a median filter and multiplying by $\frac{\lambda}{4\pi}$.
Center the filtered unwrapped phase which represents the breathing rhythm $R(t)$.
Estimate breathing frequency f_r
First method Estimate the periodogram of $R(t)$ then find the maximum.
Second method estimate the autocorrelation of $R(t)$, then find the first local maximum that gives the breathing period.
Third method Estimate the periodogram of the autocorrelation of $R(t)$.

A. SIMULATION RESULTS

In this section, results of estimating breathing rhythm and frequency are presented. Figure 1 shows an example of an estimated respiratory rhythm (top) and the graph of the estimated respiratory rate with the three methods mentioned above.

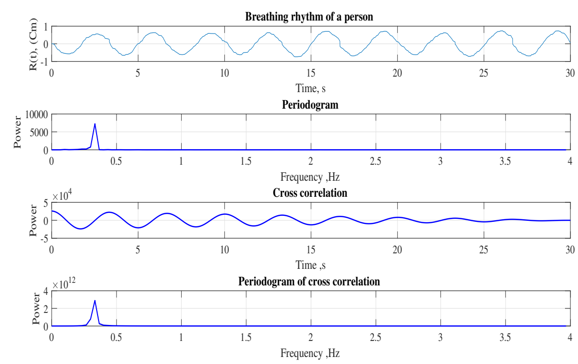

Fig. 1. Breathing rhythm and Frequency estimation with different methods.

The performance of the proposed algorithms for breathing frequency estimation are studied by calculating the accuracy and the mean square error (MSE) as described in Eq. (6) and Eq. (7) respectively, versus the SNR, which varies between $-10dB$ and $5dB$. We simulated 20 respiratory frequencies ranging from $0.2Hz$ to $0.8Hz$. Each simulated signal is 30 seconds long with a sampling rate of $4000Hz$. For each SNR we add an additive white gaussian noise.

$$accuracy = E\left[1 - |\frac{\widehat{f_R} - f_R}{f_R}|\right] * 100 \quad (6)$$

$$MSE = E\left[(\hat{f_R} - f_R)^2\right] \quad (7)$$

Figure 2 shows the variation of the accuracy of respiratory rate estimation versus the SNR. In most cases the periodogram-based method gives the least accurate result. In contrast, the other two methods generally give almost equal results with a slight difference.

Figure 3 shows the variation of the MSE as a function of the SNR. For a SNR below $-6dB$ there is not a noticeable difference between the MSE of the three methods. However, for a SNR between $-6dB$ and $-4dB$ the MSE of the periodorgram based method is worst, which have almost the same MSE. For a SNR above $-4dB$ the method based on the combination of the autocorrelation and the periodogram gives the best result and the other two give almost the same result.

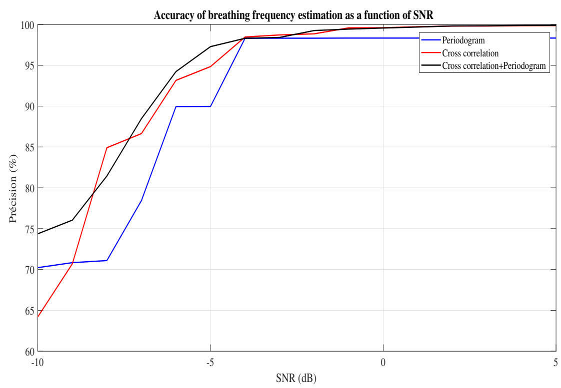

Fig. 2. Accuracy of estimation of breathing frequency versus SNR.

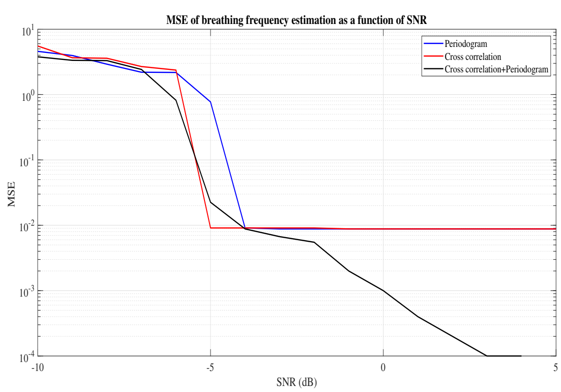

Fig. 3. MSE of estimation of breathing frequency versus SNR.

B. EXPERIMENTAL SETUP AND RESULTS

The experimental setup is based on a commercial CW radar called KMC4. This module transmits a continuous wave of $24GHz$. In our experiment the KMC4 radar is attached to a housing which is mounted on a support. Figure 4 shows a scenario where a person is breathing in front of the realized system. Note that this person is inside the main lobe of the transmitter. It sends a continuous RF wave which is reflected by the person. The chest movements introduce Doppler shifts on the reflected signal which signal is picked up by the receiver. The captured signal is demodulated by a part of the emitted signal in order to have the two channels I and Q. Inside this module, a demodulation and an amplification are made, then the I and Q components are transmitted for acquisition. In order to have a ground-truth reference while evaluating the proposed non-contact system, an accelerometer within a chest belt is exploited.

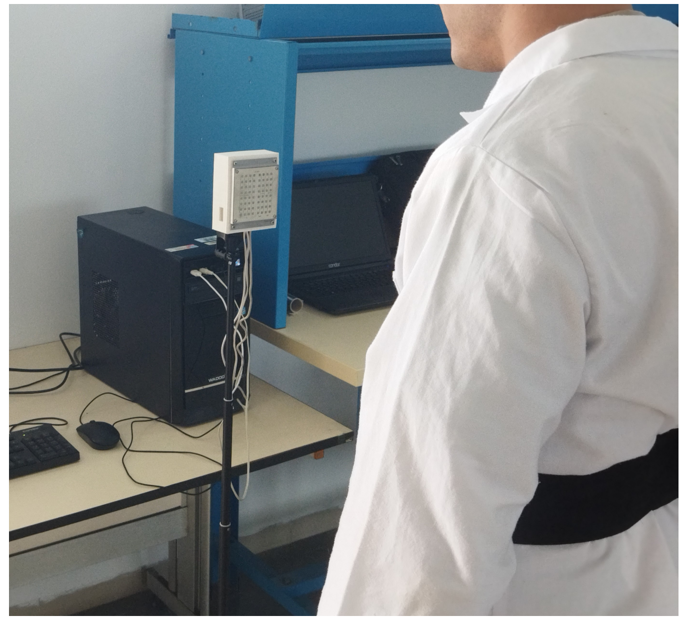

Fig. 4. Experimental setup with KMC4 radar.

several tests were carried out to evaluate the performance of this work. According to the test setup outlined in figure 4, a human target stand at distance between $0.2m$ and $1.5m$ from the KMC4 radar.

Firstly, we start with the acquisition of the I and Q signals, figure 5 shows an example of this acquired signals.

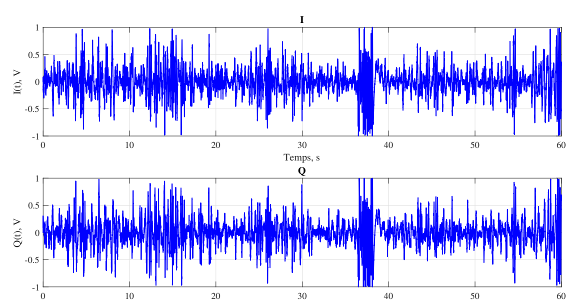

Fig. 5. I and Q signals.

In order to test the capability of the proposed system in different scenarios, three situations are considered: slow, normal and fast respiration rhythm. In each case we used a recording of 30 seconds. Figures 6, 7, 8 show the results of estimating the respiratory rhythm and the respiratory frequency by the three proposed methods: (periodogram, autocorrelation and autocorrelation + periodogram) in the cases of slow, normal and fast rhythm respectively.

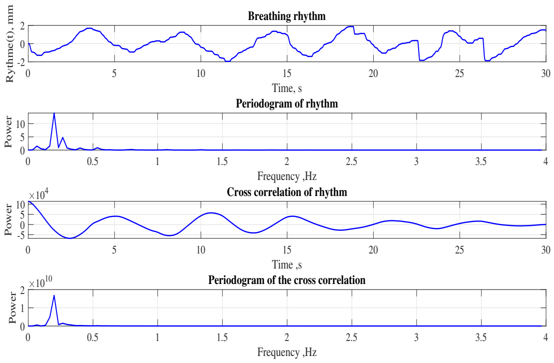

Fig. 6. Slow rhythm.

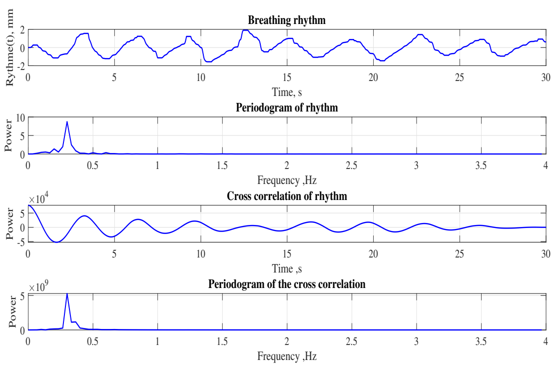

Fig. 7. Normal rhythm.

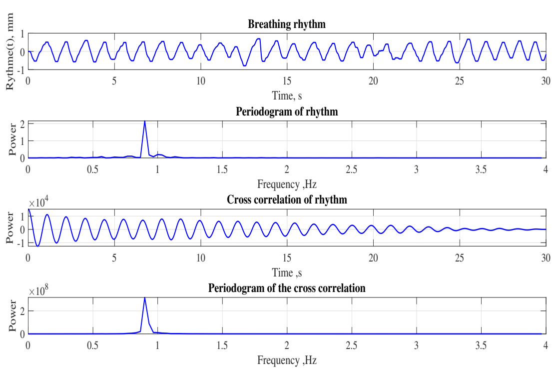

Fig. 8. Fast rhythm.

Table II gives examples of the estimated respiratory rate values for three different situations where the respiration rhythm is slow, normal and fast. For performance evaluation of algorithms applied to real signals, we used a belt that is put in the thorax, it can measure the breathing frequency using its accelerometer sensor.

Methods	Chest	method 1	method 2	method 3
Slow	0.200	0.200	0.201	0.198
Normal	0.255	0.267	0.252	0.259
Fast	0.910	0.900	0.907	0.911

TABLE II
TABLE OF BREATHING FREQUENCIES OF DIFFERENT RHYTHMS ESTIMATED BY DIFFERENT METHODS

For the comparison of the algorithms two performance criteria were used, the first is the MSE and the second is the accuracy. The table III presents the MSE and accuracy of the different methods by comparing them with the belt results. The MSE and accuracy are calculated based on $30s$ recordings of two persons, for each person we took 20 recordings.

method	MSE (Hz^2)	accuracy (%)
Periodogram	0.0014	95.40
autocorrelation	0.0003	97.12
autocorrelation+Periodogram	0.0012	95.52

TABLE III
TABLE OF MSE AND ACCURACY OF DIFFERENT ALGORITHMS

The respiration rate f_R was estimated by three methods, the first one is based on periodogram, the second one is based on autocorrelation and the third one is based on the combination of the autocorrelation and the periodogram. The results of the respiration rate estimation were compared with the belt results. The periodogram based method gave an accuracy of $95.4^{0}/_{0}$ and an MSE of $0.0014Hz^2$. The autocorrelation based method gave an accuracy of $97.1^{0}/_{0}$ and an MSE of $0.0003Hz^2$ and the method based on the combination of the autocorrelation and the periodogram gave an accuracy of $95.5^{0}/_{0}$ and an MSE of $0.0012Hz^2$. The periodogram based method gave the worst result in terms of accuracy and MSE. On the other hand, the autocorrelation based method gave the best results. The method based on the combination of the two other methods gave performances between the two. Several works have been carried out in this context. Each uses a type of radar. As well as a technique for estimating the breathing rate. Each work has its own accuracy and MSE.

To highlight our results we made a performance comparison between the results found and the results reported in the literature. A comparative analysis with relevant research efforts is presented in the table IV. Comparing the accuracy value of our work with other works in this table we note an improvement in the correlation based method which reaches an accuracy of 97.1%.

Ref and year	Type of radar	Frequency (GHz)	Accuracy %	MSE Hz^2
[7] 2012	ULB	3.2	88.9	-
[8] 2015	FMCW	80	91.1	-
[9] 2016	RF	-	88.9	-
[10] 2019	FMCW	77	94.0	-
Our work	CW	24.13	97.1	0.0003

TABLE IV
PERFORMANCE COMPARISON WITH STATE-OF-THE-ART

V. CONCLUSION

In this paper, we have proposed a non-contact breathing rate and rhythm estimation system based on CW radar. First, the phase of the demodulated complex received signal is unwrapped and filtered to estimate the breathing rhythm. The respiration rate is computed based on three methods: the periodogram method, the autocorrelation method, and the combination of both methods. Numerical simulations are conducted to show the performance of the proposed technique with its different variants. An experimental setup based on the KMC4 CW radar is used to test the efficiency of the proposed solution which outperforms the state-of-the-art.

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