Utilization of Low-Cost Pulse Coherent Radar for Physiological Assessment in vehicle Interior

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***Abstract*— Contactless human monitoring and radar have been a discussion topic in vehicular technology. This technology applied to interior monitoring may open new opportunities for assistance systems that provide information about the passenger's health condition. This paper characterizes the usage of a low-cost single radio-frequency pulse radar as a mean to assess driver's respiration and heart rate inside a vehicle. Real data acquisition was performed and the accuracy of the radar evaluated against a ground-truth (ECG). Two signal processing techniques were applied and in each proposed scenario: Short Time Fourier Transform (STFT) and Empirical Mode Decomposition (EMD), where STFT presented a better curve fitting and higher accuracy.**

***Keywords*— Radar, vital signal, signal processing, physiological supervision**

I. INTRODUCTION

Radars are used to detect and track objects, and it is a promising technology in the studies of autonomous driving and Driver Assistance Systems (DAS) [1]. Investigations focusing on the sensor benefit from both classical signal processing techniques and machine learning approaches. Before proceeding to the more current AI methods, it is necessary the investigation with state of the art techniques in order to assess points of improvement, when necessary. In terms of the investigation of human monitoring and physiological state - the aim of this work - usually Continuous Wave (CW) or Ultra Wide Band (UWB) radars are used [2], although these sensors are expensive and very energy consuming. In order to overcome these restrictions, this research analysed the use of a low-cost and low consumption pulse radar at the task. The sensor is approximately 3x more economical than the second comparable sensor in the market and provided open user interface and access to the collected data.

This paper is divided in the following structure: first a general review on the topic and premises assumed, presented in this introduction section, followed by a review of the radar systems in section 2. Section 3 presents the methodology for the experiments and section 4 about the processing techniques for the signal. Finally, Section 5 and 6 bring the results and discussion and the conclusion, respectively.

II. RADAR

The radar is a sensor that detects targets based on the receipt of reflected echoes from transmitted RF pulses. The receiving antenna detects this backscattered signal and based on this information, it is possible to measure the target's distance, relative velocity and angle. The energy received by the radar depends on a series of properties from the radar itself and the target.

A. Pulse Radar

The pulse radar is an intermittent time-of-flight sensor, providing measures based on the time the echoed wave takes to return. The radar emits from the first antenna the electromagnetic waves (EM) of very short time duration, or pulse width, then the signal is received by a second antenna, ceasing the transmission. The sum of the time to transmit and receive the signal is time cycle or Pulse Repetition Interval (PRI). The Pulse Repetition Frequency (PRF) is the number of cycles completed per second and measured in Hz and it is the inverse of the PRI [3].

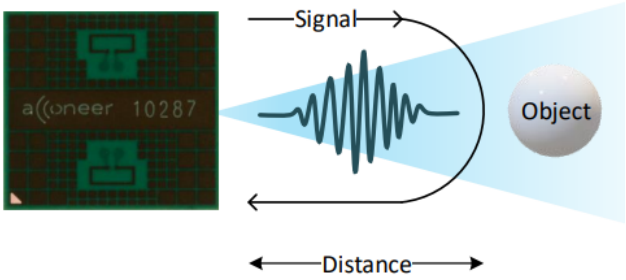

Fig. 1. Monostatic radar [4]

The distance from the target is calculated multiplying the the time-of-flight by the speed of the radio wave and dividing it by two - the wave runs twice the distance to the target, forward and back [4]. If the target is at a distance such that the time for the wave round-trip is bigger than the Interpulse Period (IPP), a mismatching of reflections will occur, called range ambiguity. The IPP is the time between emissions and in this case, the returned EM will not arrive before the next pulse is emitted, leading to a confusion between a reflection from a close target to the reflection of previous pulse coming from a distant one [3].

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B. *Doppler effect*

The Doppler effect or shift is the change in frequency of a backscattered signal that is moving regarding the source of the signal. The presence and the speed of the moving object can, then, be obtained from this difference in frequency between the transmitted and received radio wave [**?**].

C. *Health concerns*

When using a radar inside the vehicle, one has to be sure of the equipment's innocuity. When working with radio waves, which is considered as a low-frequency radiation, the extended exposure to an intense enough field can cause the target's molecules to vibrate, producing heat and, in large scale, burns. Considering the pulse radar used in the present study, the intensity field of the electromagnetic wave is measured in W/m^2, causing harm above 1000 W/m^2. The normative US/FCC 47 CFR part 15 regulates the requirements for radio spectrum usage and sets the maximum permissible exposure at 20 cm to be 0,1 W/m^2. The Acconeer radar is approved by this regulation and also tested against the European Union normative (UE/CEPT) of The European Commission Radio Equipment, which confirmed that the equipment respects the limit values given. More information on the test results can be found at [4].

III. RELATED WORKS

The detection of heart and respiration rate with radar overlaps with other applications that aim to detect presence and motion of human targets. A 1.6 GHz CW radar was used by [5] to detect respiration and heart rate behind a wall, such application is applied in search and rescue missions after an incident, due to the capacity to detect across rubbles. The same scenario was investigated with a different working band, 4 to 7 GHz and an UWB radar, by [6]. In the medical field, a more direct approach is preferable, though, when working with human supervision, higher frequencies were used. In [7], the output of a 16GHz CW radar was compared with an ECG and [2] used a 24GHz to investigate the affect of different radar positions to assess the respiration and heart function. With the advancements in radar technology and the usage in this application, the lower frequencies have been set aside and higher frequencies adopted as a standard, due to the narrow band interference and null detection points that happen at lower bands. In this trend, the present research focus in a higher radio frequency, aligning it to the pulse radar technology, which consumes less energy - important factor due to the nature of the application. Also it allows for performance comparison with previous works with CW radars in similar conditions.

IV. METHODOLOGY

The research aimed to evaluate the accuracy of a low-cost pulse coherent radar in assessing the heart and respiratory rate of passengers in a vehicle. This work supports the evaluation of the trade between mobility and accuracy in the measurement of the physiological parameters that comes with the use of a direct measurement (ECG) and indirect measurement (radar). For that, use cases were discussed and proposed and, then, real tests executed in the laboratory.

The equipment used was an Acconeer$^{\text{TM}}$ XM112 monostatic radar module sensor and XB112 breakout board. The radar has a carrier frequency of 60.5 GHz, with bandwidth from 57 to 64 GHz, the used range of the measurement was between 0.2 and 0.8m and the sampling frequency of 20 Hz. The Acconeer radar is coherent, in which due to the processing structure allows to obtain both the amplitude and the phase of the signal, the in-phase and quadrature, in this manner, the resulting acquired signal is a complex value, allowing the detection of finer movements with the μm precision and efficient noise cancellation [8].

The measurements were performed inside a vehicle with the radar was fixed directly in front of the driver's seat, in the windshield, by a suction cup and a PLA structure (designed in Catia V5$^{\text{TM}}$ and 3D printed), in such a fashion that it was possible to adequate the angle of the sensor accordingly to the subject. The equipment was adjusted in order to stand in a 90○ from the subject's chest. The distance between the radar and the subject was approximately 0.6 meters. As ground-truth, an ECG device (shimmer3) was used to perform accurate heart rate and respiration rate measurements. A homogeneous group of subjects was asked to take part in the experiments to decrease the effect of physiological characteristics. The group was then composed by 10 males, between 20 and 45 years old. First, subjects were briefed about the goals and structure of the evaluation and patched with the electrodes on the chest. The experiment lasted one unique session (approximately 30 min.), where five measurements were made in three distinct scenarios. For all scenarios, the subject was seated on the driver seat (siting angle approximately 110°, facing the radar):

1) Measurement 1: Subject breaths normally for 60 seconds (scenario 1);
2) Measurement 2: Subject holds breath for as long as he can (scenario 2);
3) Measurement 3: before performing the measurement, subjects steps out of the vehicle and performs 1'30" of cardio exercise, to increase heart frequency. Immediately after, subject returns to the vehicle and measurement is performed for approximately 1 minute (scenario 3);
4) Measurement 4: repetition of scenario 1;
5) Measurement 5: repetition of scenario 2.

The evaluation between sensors was made by calculating the root-mean-square (RMSE) of both dependent variables (heart and respiration frequency) from both sensors (radar and ECG). Two evaluations were held, first using the mean frequency for a 15 and 10 seconds warm-up time window and then, for the complete signal point-to-point, after the warm-up time. In order to evaluate both signals together, they were synchronized along the radar timestamp.

V. SIGNAL PROCESSING

All algorithms used to process the radar data were built in Matlab. Python was used for applications related with the ECG data processing and visualization, using Biosppy [9] library.

A. *Data structure*

The radar data structure is dependent on the distance of measurement, where each bin has approximately 0.5mm, which is the range resolution [4]. Based on the selected parameters, the resulting frequency resolution for 10 seconds is 0.100 Hz and for 15 seconds is 0.067 Hz. As Figure 2 illustrates, the distance is represented in the M axis (fast time). The time duration, and Doppler shift, on the N axis (Slow time), increases the number of pulses, thus, yielding an NxM matrix. Figure 2 also shows two targets, one in the same resolution bin (target 1) and one moving in different resolution (target 2). Fast time means the velocity of acquisition of each range bin inside a pulse and slow time is the time between pulses.

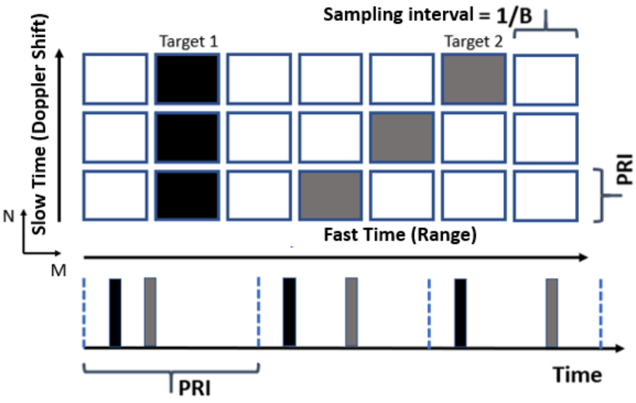

Fig. 2. Radar matrix structure (being B: bandwidth and PRI: Pulse Repetition Interval)

VI. SIGNAL PROCESSING

The first step in the processing is to find the position of the target, and this is done with the envelope of the signal. Taking in the in-pulse direction, where the point with the highest energy is taken as the position of the target. At every iteration, this position is recalculated in order to find the position for the new measurement. The position of the target is considered fixed throughout the duration of the time window, due to the characteristics of the measurement. The pulse taken for the position analysis is always the last pulse of the window.

A. *Short Time Fourier Transform algorithm*

The STFT is the first method to find the heart and respiratory frequencies, it searches the frequency spectrum for the highest energy peak, after applying the FFT in the selected window, in the slow time direction (N axis on Figure 2). This STFT is applied in the column which corresponds to the detected presence of the target. In order to clear the spectrum peaks, several windowing methods were investigated with the Blackmann window providing the best results.

In order to prepare the signal to the STFT, a series of pre-processing steps were applied, first removing the DC component and applying an IIR Butterworth band-pass filter between 0.12 and 2.5 Hz. Then, the windowing and STFT to estimate the frequency components search for the frequency corresponding to the highest energy peak. This peak is taken as the respiratory frequency.

For the Heart rate a similar process is applied, due to the ratio of magnitude of the breathing to the heart signal, the first needs to be removed from the signal. Ergo, a notch filter removes the respiratory frequency and up to its 4th harmonic before proceeding. The same pipeline as for the breathing is used, now with a band-pass filter with cut-off frequencies of 1 ans 4Hz, followed by the windowing and STFT and estimation of the heart frequency.

B. *EMD with Euclidean distance*

The Empirical Mode Decomposition is a non-linear method that allows the separation of the observed signal into its Intrinsic Mode Functions(IMF) and a residual function, where each IMF represents one vibration mode. The Euclidean distance is used to compute the distance of the original signal to each IMF, to select which oscillatory mode represents the signal more faithfully.

As for the STFT, the same pipeline is used until the separation of the frequencies - for STFT- and here, the IMFs. The EMD was applied in the same window of signal after the pre-processing and then a Blackmann window was applied to each IMF, in order to calculate its frequency. The Euclidean distance then is used to select which IMF is taken as the respiratory rate. The notch filter is applied, then, to remove the respiration frequency and its harmonics from the signal and the pipeline is used again to find the heart rate frequency.

VII. RESULTS

This section presents the achieved results and provides an analysis and debate on the performances. The information extracted from the signal with the two proposed methodologies are compared to the ECG for all 10 subjects and proposed scenarios. To illustrate the process, one example of heart rate signal of a random target is shown with the results. First the results are presented for a single window of time, revealing the average frequency and later the comparison throughout the entire signal, with the dynamic shift of the time window.

The time that the sensor takes to provide the first quality measure is called warm-up time, the two proposed time windows (10 and 15 seconds) were considered to evaluate which provided a higher accuracy and with which methodology. The Biosppby library [9], on python, was used to select the best QRS complex match, the heart pattern detected by the electrode lead.

A. *Analysis procedure for one subject*

The first step in the evaluation for the single window of signal is to process the ECG signal in the selected window, illustrated ahead with with 10 seconds for scenario 1 and heart frequency. The raw ECG signal was windowed with a Hamming window and then an FFT was applied to verify the frequency components.

Then, for the radar, using the described processing pipelines, the analysis of the respiratory rate for scenario 1 and in window of 10 seconds was performed. For the ECG, the found value was of 0.300 Hz, corresponding to 18 respiration per minute (RPM). Using the STFT method, the analysis shows that the radar points to a respiration frequency of 0.260 Hz, signalizing 15.6 RPM. The comparison between measures evidence an error of 13.30%, 2.4 RPM.

For the EMD, three modes of vibration were found, presenting frequencies of 0.200, 0.200 and 0.200 Hz. With the Euclidean distance, IMF 1 was taken to be the signal of interest and then the respiration frequency, 0.2 Hz. This measure points to an error of 30%, with 6 RPM.

The time and frequency domain signals of the ECG for the heart rate can be observed in Figure 3. The energy peak of the spectrum is found at 1.100 Hz, which corresponds to 66 BPM and is taken to be the ground-truth.

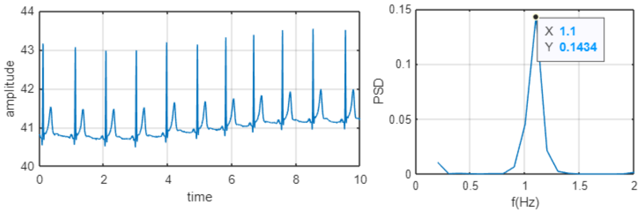

Fig. 3. ECG heart signal filtered (left) and on frequency domain (right)

After the removing the harmonics of the respiratory rate found in the first step, Figure 4 shows the results of the radar processing using the STFT method on the correspondent time window. The left instance presents the signal in the range bin in the time domain while the right instance, the behavior in frequency. The highest energy peak in frequency is found at 1.100 Hz, corresponding to the exact value found at the ECG.

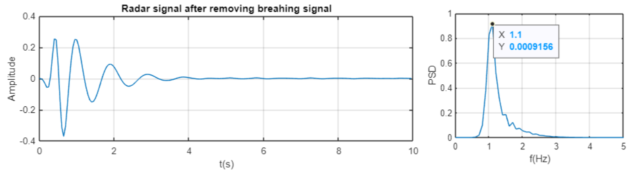

Fig. 4. Radar signal raw (left) and on frequency domain (right)

In the same window, with EMD, the frequencies of each vibration mode are 1.100, 1.000 and 0.4000 Hz, Figure 5. Using the Euclidean distance, the IMF 1 is closest to the original radar signal and it is taken as the interest signal, 1.100 Hz and 66 BPM. In this case, as the STFT, the EMD also matched exactly the ECG, without errors.

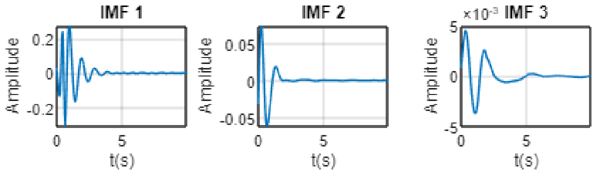

Fig. 5. image/Intrinsic mode function of the radar signal

B. Mean Heart Rate (HR) and Respiration Rate (RR)

The methodology described in the previous section was applied to the entire subject group and scenarios: regular breathing (scenario 1), holding breath (scenario 2) and panting after exercising (scenario 3). The evaluation was held for both warm-up times and the summary of the average error throughout the measures and between sensors is presented in Table I.

For the respiratory rate (RR), in the 10 seconds analysis, the STFT presented superior performance with lower average error but higher standard deviation. Nonetheless, EMD performed better in scenario 1. Likewise, in the results from the 15 seconds window, the outperforming method in the first and third scenario was the EMD, with smaller errors, but higher standard deviation.

The STFT outperformed in all three scenarios for the heart rate at 10 seconds, with scenario 1 presenting the lowest deviation from the ground-truth and scenario 3 presenting the highest heart rate error values. At 15 seconds, comparatively with the smaller window, the extracted values presented a higher deviation from the ground-truth. STFT again presented a better performance, but with scenario 3 presenting the lowest accuracy.

In general, the 15 seconds window was outperformed by the smaller counterpart, presenting higher average error for both procedures. For the heart rate, the STFT was superior in both warm-up times, having better performance in 10 seconds, while the respiration had a better performance with EMD and 10 seconds. All mean error values for both methods and all scenarios are presented in Table I.

Window	10 seconds				
Scenario	Breathing		Not breathing	Exercise	
Measurement	HR	RR	HR	HR	RR
STFT error (%)	7.09	19.31	11.56	15.23	13.47
Std STFT (%)	5.57	7.88	5.72	10.46	12.39
EMD error (%)	13.81	17.14	13.47	16.98	15.35
Std EMD (%)	9.93	16.57	5.91	8.55	12.2
Window	15 Seconds				
Scenario	Breathing		Not breathing	Exercise	
Measurement	HR	RR	HR	HR	RR
STFT error (%)	10.65	26.28	12.97	14.30	23.18
Std STFT (%)	4.54	8.91	6.04	7.98	9.26
EMD error (%)	12.12	19.20	16.74	14.77	16.95
Std EMD (%)	5.89	11.47	8.73	9.99	13.54

TABLE I

MEAN ERROR VALUES

C. HR comparison across time

In order to track how the heart rate measurements changed across time a comparison was made, point to point, using both windows of 10 and 15 seconds, the three measured scenarios and both analysis methods. Table II shows the values for the absolute mean error, the relative error, the RMSE and standard deviation of the measurements.

STFT

Scenario	Window	Absolute	Relative (%)	RMSE	Std
Breathing	10s	11.48	22.46	32.50	11.73
	15s	9.46	13.75	22.27	9.76
Holding Breath	10s	11.02	14.76	23.44	10.367
	15s	10.05	14.29	16.73	8.37
Exercise	10s	13.00	17.16	40.03	12.97
	15s	9.78	19.95	23.10	9.64

EMD

Scenario	Window	Absolute	Relative	RMSE	Std
Breathing	10s	11.35	16.75	36.28	13.20
	15s	10.95	16.20	26.34	11.71
Holding Breath	10s	12.00	16.87	29.93	12.56
	15s	11.69	16.73	21.28	9.86
Exercise	10s	12.43	17.92	40.69	14.31
	15s	9.11	15.46	26.20	11.71

TABLE II

MEAN ERROR VALUES - COMPLETE SIGNAL

Based on Table II, it is possible to observe that the 15 seconds warm-up time outperformed the smaller window at every metric. In general, this is expected due to the increase information held within the signal. The absolute error values did not vary greatly between scenarios but the RMSE value demonstrated that for higher HR, both methods have difficulties adapting at the smaller time window.

VIII. CONCLUSION

This study investigated the feasibility of use of a low-cost pulse radar inside vehicle as a mean to assess the physiological state of the driver. Real radar detection from a group of subjects were performed in real conditions in order to achieve a the best representation of a real life situation.

This paper proposed an analysis of the trade-off in mobility and accuracy between direct and indirect measurements of HR and RR. In order to do so, two algorithms pipelines of classic signal processing techniques were developed, STFT and EMD, as a mean to assess the influence of the non-stationarity characteristic of the signal with linear and non-linear methods, as well. The final results endorse the idea of radar as a human monitoring tool and points to the possibility of lowering costs and consumption with the application of the pulse coherent technology in the automotive context.

Tables I and II present the performance values for EMD and STFT, it is possible to observe that, although the absolute accuracy provided by both methods are similar, STFT presents a smaller RMSE, meaning a better fitting of the curve. In the first scenario, both warm-up times presented a high mean error value and variability. A similar behavior was found in the third scenario as well. Additionally, all scenarios presented, for the heart rate, a higher accuracy at 15 seconds, in both methods.

Still for the single window, comparing the both signal processing approaches, at the smaller warm-up time window, the heart rate was better represented by the STFT, overall. On the bigger window, the EMD provided a more reliable measurement of the HR, and, even at the worst scenario (panting), it showed improved results.

However, for the complete signal, STFT is more reliable throughout the results, especially for a bigger window. The found results are consistent with the literature prediction for classical methods and CW radars. This points to the capacity to perform the designed task under certain conditions using a cheaper and less energy consuming sensor. At this point, the indirect measurement is about 14% deviated from the direct measurement, but it is positive sign for the field.

In order to achieve a desirable accuracy for the measurement, other techniques can be applied with the system. For the time being, this work demonstrated that is possible the application of this pulse coherent technology in human assessment with positive output, under controlled circumstances as an alternative sensor.

In order to further develop the system, some prospects for future works that rose during the analysis are indicated. The method of frequency peaks selection should be improved, especially in spiked frequency spectrum. The presence of other movements in the same frequency range as the interest information dilutes the signal and can lead to measurement errors. For the respiration, for instance, one alternative to improve its result is the evaluation of distance of the chest and tracking of its movement and phase shift, as observed in the graphical interface of the radar kit [4].

Using conventional range-Doppler imaging, associating an FFT shift with the current methodology applied here, it is possible to estimate the Doppler shift profiles. This technique associated with a 2D-CFAR algorithm may possibly be able to detect both HR and RR in the same range bin, without having to split the signal. Taking that the SNR of the interest signal is relatively high, the investigation might resume satisfactory results.

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