Evaluation of a Low-Cost COTS Bio Radar for Vital Signs Monitoring

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***Abstract*—With the beginning of the COVID-19 pandemic, there was a need for the Health Care Workers (HCW) to pay more attention to the vital signs of their patients. One way for this to happen, while respecting the social distance, is using contactless technologies, e.g. the bio radar. This way, the HCW will be able to monitor the respiration and heart rates of the patient, without getting close to him. For this to be possible, the best radar configurations were studied, as well as other important aspects that should be taken into consideration while monitoring a patient, for the results obtained to be reliable.**

***Index Terms*—Bio Radar, FMCW radar, COVID-19, Vital Signs Monitoring, Heart Rate, Respiratory Rate**

I. Introduction

The end of the year 2019 was marked with the discovery of a new coronavirus, the SARS-CoV-2 or COVID-19. Being airborne, this new virus is highly infectious and, as of March 11, 2020, was declared a pandemic [1]. As such, preventive measures were created and implemented worldwide to reduce the number of infected. These measures include social distancing and increased hygiene standards. However, HCW, being at the front line of the fight against the virus, have a higher infection risk since many health care procedures need direct contact with the patient, increasing the probability of infection. As of May 8, 2020, about 152888 HCW were registered to be infected and about 1413 HCW died [2]. One way to reduce contact between patients and medical staff could be to monitor their vital signs during a routine checkup at a distance using contactless technologies, such as the bio radar.

A bio radar uses a radar to monitor a subject's vital signs by measuring differences in the received signal's phase. These phase differences are caused by displacements in the patient's chest due to respiration and heartbeats, which can be used to calculate the cardiorespiratory rates.

The concept of non-contact extraction of human physiological parameters has been demonstrated by pioneers in the 1970s [3]–[5], where the respiration was measured along with the heartbeat during apnea interspersed periods. Thenceforth, several solutions have been presented using different Radio Frequency (RF) front-ends, using combined components such as in [6,7], or even using more compact solutions provided by a Software-Defined Radio (SDR) as shown in [8].

In [9,10] is presented a state-of-the-art of bio radar hardware implementation, which gathers several solutions that have been presented in the literature. Nowadays, the research in this area is more and more focused on the improvement of the current system implementations, exploring solutions with features that guarantee low power, small dimensions, better accuracy, long-range detection, and a more robust operation. The ability to adapt these systems to any environment is even more appealing, due to the wide range of bio radar applications. In this sense, SDR is a suitable hardware approach, since it is compact and allows the digital configuration of its input and output (receiver and transmitter), regarding the required frequency and sampling rate of the target application [8].

Nowadays, some radar technologies are available in the market with customized products for bio-signals acquisition. Among the options, different radar operation modes and carriers are being used, where it is possible to highlight the Ultra-Wideband (UWB) radars operating at sub-10 GHz [11], Frequency Modulated Continuous Wave (FMCW) transceivers using 24 GHz [12] or 77 GHz [20], or finally, stepped frequency Continuous Wave (CW) radars operating at 3.6-4.0 GHz [13]. This fact raises doubts regarding which is indeed the best Commercial-Off-The-Shelf (COTS) hardware solution for the transceiver and which is the best carrier frequency for the problem at hand.

More recently [14] presents a detailed review, which aims to define guidelines that might be followed commonly in every bio radar implementation, regardless of the application. In [15] the authors present a novel cough detection system using a 24 GHz K-band continuous-wave Doppler radar sensor along with a Convolutional Neural Network (CNN) architecture.

This paper evaluates the reliability of a low-cost COTS bio radar, based on an FMCW architecture, for contactless measurement of heart and breath rates in scenarios such as continuous vital signs monitoring, or routine checkups. The radar evaluated in this work was selected among several COTS devices after a multicriteria analysis, cf. Section II, which

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resulted in the selection of the AWR1642BOOST evaluation board from Texas Instruments, operating at a frequency range of 76 to 81 GHz.

The remainder of this paper is arranged as follows: firstly, an introduction to relevant topics related to the bio radar under evaluation is presented in Section II. Afterwards, the experimental procedure is introduced to maintain uniformity between tests in Section III. The results obtained are presented and discussed in Section IV and, finally, conclusions and suggestions for future work are presented in Section V.

II. Background

In this section, the main features of the vital signs under measurement are presented, and the operation principles of a bio radar are introduced. In addition, some operational bio radar specifications are presented, as well as a small comparison to other COTS bio radars. To finalize this section, the radar equation, and other relevant Doppler radar tools, are introduced.

A. Vital signs monitoring using Doppler radars

A subject's vital signs can be monitored with a Radar by sending an RF signal and obtaining the phase from the reflected signal. By obtaining different phase values in a time interval, it is possible to use different algorithms to calculate both the heart rate and the respiratory rate. Table I presents the characteristics of the vital signs in adults, including both the amplitude and the frequency. Due to the vital's small amplitude, it is preferred to measure the radar's received signal phase shift instead of the frequency shift, which would be barely noticeable.

TABLE I
Characteristics of the different vital signs [29].

Vital Signs	Frequency [Hz]	Amplitude [mm]
Breathing Rate	0.1-0.5	1-12
Heart Rate	0.8-2	0.1-0.5

One advantage of FMCW radars over CW radars is the possibility of detecting also the distance to the target, discarding possible reflections from unwanted sources, providing a clearer received signal. Another aspect that should be taken into consideration is the frequency of operation of the radar, i.e. higher frequencies lead to increased sensitivity to small displacements. For example, radars operating at 77 GHz can detect movements in the order of millimeters. However, a higher resolution also means that small involuntary movements from the subject will be detected, possibly degrading the signal.

B. Hardware Selection / Characterization

The radar evaluated was the AWR1642, from Texas Instruments. This chipset has an embedded microprocessor, to run the main application and a Digital Signal Processor (DSP) to run calculations in parallel with the main application without the need for a computer.

The AWR1642BOOST is the evaluation board used in this work, which contains two transmitting antennas, spaced 2λ between themselves and four receiving antennas, spaced $\lambda/2$ [18]. Each antenna is composed of a linear array of four patch antennas working on a frequency range from 76 GHz to 81 GHz, an overall gain of 9 dBi, and a maximum transmitting power of 12 dBm. This evaluation board supports using these antennas in MIMO configuration, effectively creating eight virtual receiving antennas by alternating which transmitter antenna sends the chirp [18]. However, the support guide for the vital signs demo notes that enabling MIMO would only be useful to detect multiple subjects. By enabling both transmitting antennas, with a phase shift of 0 degrees and sending the same chirp at the same time, it should work as a multidimensional array of antennas, increasing the gain and decreasing the half-power bandwidth, creating a more directional beam.

TABLE II
Comparison of the specifications of different radar evaluation boards.

Board Name	Frequency [GHz]	Architecture	Price	Ref.
AWR1443BOOST	76 - 81	FMCW	\$299	[19]
AWR1642BOOST	76 - 81	FMCW	\$299	[20]
AWR6843ISK	60 - 64	FMCW	\$149	[21]
OPS241-A	24 - 24.25	CW	\$169	[22]
OPS241-B	24 - 24.25	FMCW	\$169	[23]
EV-TINYRAD24G	24 - 24.25	FMCW	\$1800	[24]
EV-ADF5902SDIZ	24	FMCW	\$500	[25]
POSITION2GO	24 - 24.25	FMCW	\$286	[26]

With Table II it is possible to justify the selection of the AWR1642BOOST evaluation board, since it is based on a radar that has the highest frequency of operation (resulting in higher sensitivity), uses an FMCW architecture, and is low-cost. Moreover, since the AWR1443BOOST evaluation board has similar characteristics, it can also be a viable possibility.

C. Radar Equation and Link Budget Analysis

The total attenuation suffered by the transmitted signal can be calculated using Friis formula [27], which is presented in Equation 1,

$$Pr_{[dBm]} = Pe_{[dBm]} + Ge_{[dBi]} + Gr_{[dBi]} - Lps_{[dB]} \quad (1)$$

where Pr is the received power, Pe is the emitted power, Ge and Gr are the emitting and receiving antenna gains, respectively, and Lps is the free space loss. Lps can be calculated using Equation 2.

$$Lps_{[dB]} = 32.4 + 20\log_{10}(d_{[km]}) + 20\log_{10}(f_{[MHz]}) \quad (2)$$

where d is the distance that the signal travels and f its frequency. It should be noted that for this application, the distance the signal travels is two times the distance from the radar to the subject.

The phase shift, in radians, caused by a displacement ΔR can be calculated using equation 3,

$$\Delta\phi = \frac{4\pi}{\lambda}\Delta R \tag{3}$$

where λ is the wavelength. As said before, it is possible to notice that, since higher frequencies have a smaller wavelength, the increase of frequency of operation would increase the sensitivity.

III. Experimental Procedure Description

To maintain a standardized test environment, an evaluation procedure was designed. With the subject sitting at a distance d from the radar, the maximum distance in which good results were achieved was 1 meter, cf. Figure 1. Moreover, it is important to guarantee that the radar receiving antennas are aligned with the patient's heart, to obtain a better heart rate accuracy. Failure to guarantee this alignment reduces the quality of the overall results and may cause the resulting heart rate values to oscillate around a central point.

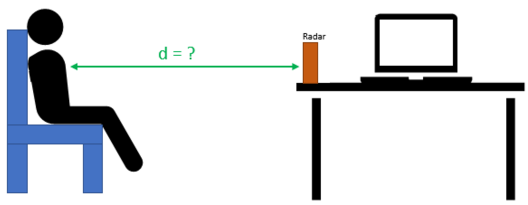

Fig. 1. Experimental Procedure Diagram.

The test should be done with an additional reference sensor to validate the obtained results, preferably a chest band capable of measuring both the heart and breathing rates. In this work, a BIOPAC MP36 reference instrument equipped with a chest band was used. The BIOPAC MP36 is a certified acquisition board capable of measuring various physiologic signs, and can be used with various accessories, chest band included. A smartwatch, model SM-R720 from Samsung [28] known as Gear S2, was also used to evaluate its reliability. Once the measurement starts, the subject should stand still for about 15 to 20 seconds so that the radar can output stable results. Table III introduces all the experiments undertaken, which will be described in detail in the next subsections.

TABLE III
Description of the different experiments.

Experiment	Description	Distance [cm]
A	BIOPAC and Smartwatch	N/A
B	Clear Signal	60
C	Signal with artifacts	50
D	Alignment issues	90
E	Number of TX antennas	70
F	Receiving gain	60
G	Maximum distance	100

IV. Experimental Results

In this section, the results obtained using the experimental procedure defined in Section III are presented. In these results, it will be possible to verify the influence that the radar alignment with the patient's heart has on their measured vital signs, the behavior of the radar with increasing distances, what impact the gain of the reception block has on vital signs measurement and evaluate the influence of the number of transmitting antennas on the measured signals.

A. Experiment A

In this experiment, a smartwatch, in this case, the Samsung Gear S2 was compared with a reference instrument, i.e. a BIOPAC MP36, to evaluate the reliability of the smartwatch. Since the smartwatch is only able to obtain the heart rate, the respiratory rate was discarded in this experiment. The acquired heart rates are presented in Figure 2. As it is possible to observe, both heart rates followed the same tendencies, however, due to the high sampling frequency of the BIOPAC MP36, set to 2 kHz, the obtained heart rate signal has higher resolution and presents small variations. However, these variations can be filtered using a moving average filter and then a signal decimation can be performed.

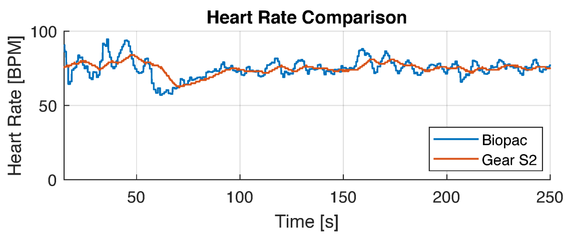

Fig. 2. Heart rate from BIOPAC and Smartwatch.

B. Experiment B

In this experiment, the radar was compared with the reference instrument, i.e. a BIOPAC MP36. The experiment was performed with the patient at a distance of 0.6 meters from the radar and the results are presented in Figure 3.

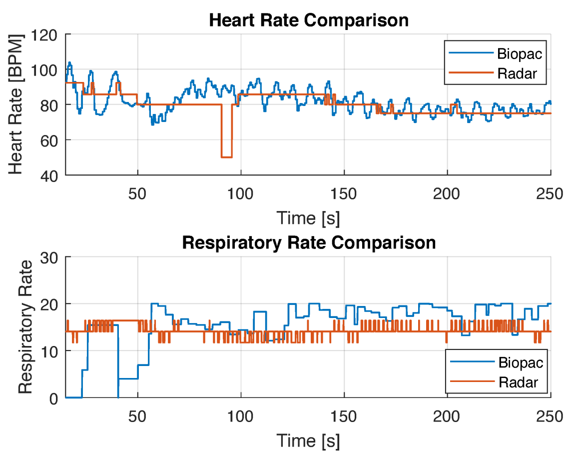

Fig. 3. Heart and respiratory rates from BIOPAC and Radar.

From the obtained results, it is possible to observe that the radar achieved acceptable results when compared to the BIOPAC, although the respiratory rate obtained by the radar is slightly below the reference instrument. The resulting relative mean error is about 6.7 % for the heart rate and 20 % for the breathing rate. The high breathing rate error is due to the resolution that the radar has, since it only increments in steps of 2.5 breaths per minute.

C. Experiment C

This experiment was meant to test the sensitivity of the radar to some degree of movement. In this instance, the subject rotated his torso 90 degrees to the right from 100 to 130 seconds, after which the subject returned to the original position. As the results obtained show, cf. Figure 4, slightly after the movement was performed, and for the rest of the test the radar was not able to get a stable heart rate signal. This failure to get a stable heart rate signal could have been caused by a heart alignment miss when the subject returned to the original position.

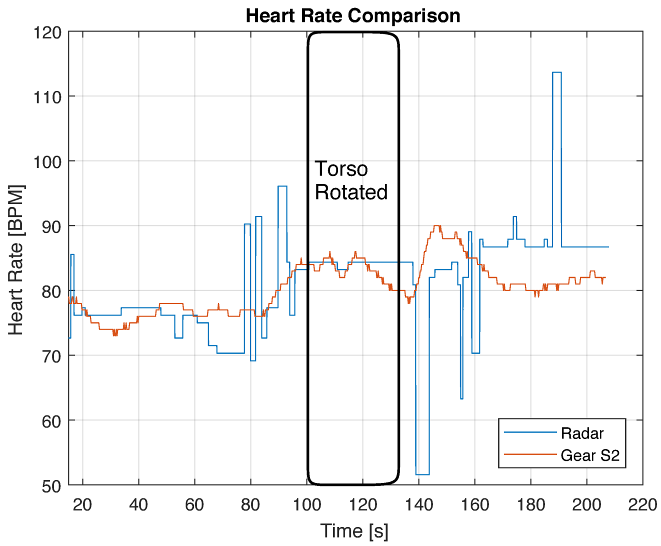

Fig. 4. Heart rate with artifacts from Radar and Gear S2.

D. Experiment D

One aspect that was thought of as important was the alignment of the radar with the subject's chest. Since the heart beat signal has a small amplitude variation, when compared with the breathing signal, the alignment with the heart is important. As such, an experiment was carried out to understand the impact of the alignment where Figure 5 shows a sample from a signal where there was a misalignment until 50 seconds during the experiment. As it is possible to observe before the alignment was corrected, the radar was unable to get a correct heart rate signal. However, 33 seconds after the alignment correction, the radar managed to get a stable signal.

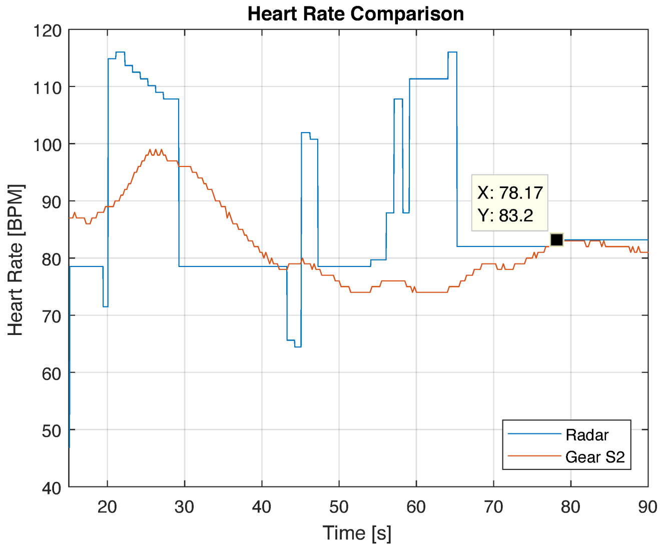

Fig. 5. Heart rate with alignment issues from Radar and Gear S2.

E. Experiment E

In this experiment, the influence from the number of transmitting antennas was evaluated. Several tests were performed over the same scenario and under the same measuring session to reduce differences from a slightly different scenario.

As shown in Figure 6, although the test with two transmitting antennas deviates from the smartwatch results near the end, the signal has more stability over time than the signal obtained in the test with only one transmitting antenna.

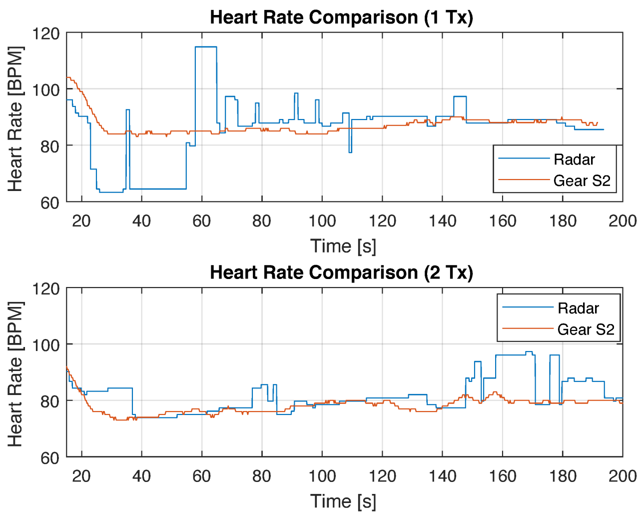

Fig. 6. Heart Rate results in function of transmitting antennas.

F. Experiment F

After examining the radar evaluation board configurations and noted that it allows changing the receiving gain, some tests were conducted with different gains. The results obtained can be seen in Figure 7. From the results obtained it is possible to observe that a bigger receiving gain can worsen the heart rate signal. This may be caused by a noise power increase, overpowering the small amplitude of the heart rate signal.

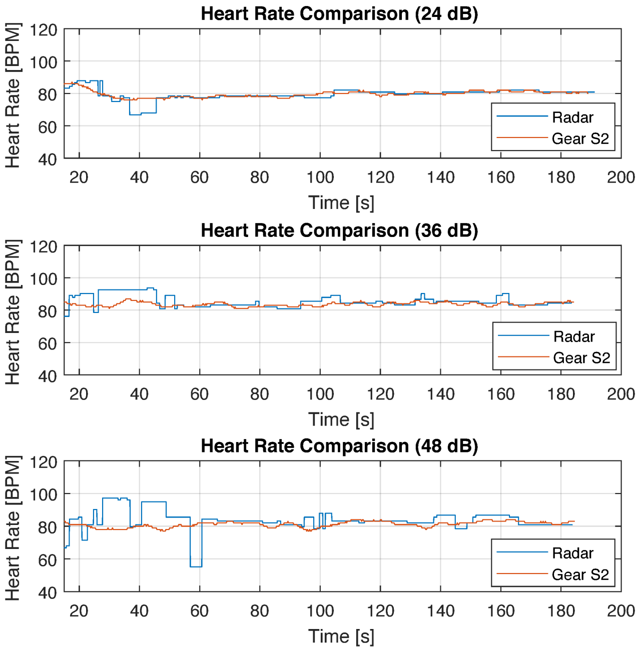

Fig. 7. Heart Rate results from Radar and Gear S2.

G. Experiment G

Finally, an experiment was performed to evaluate the maximum operating distance, i.e. the maximum distance between the radar and the patient that can be used to detect the radar signals and compute the vital signs rates with confidence. It was observed that at one meter the radar was still able to detect the heart and respiratory rate with success, as depicted in Figure 8.

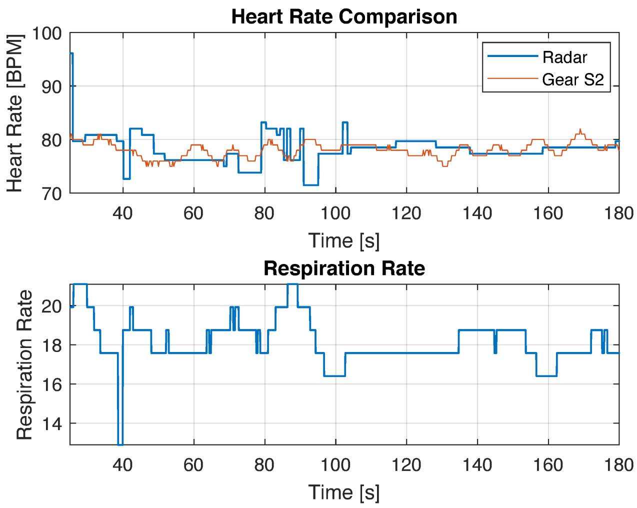

Fig. 8. Heart and Respiration rate results from Radar at 1 meter.

As presented in Figure 8, the heart rate signal obtained by the radar oscillates around the result from the smartwatch. Note that, the rapid variations coming from the radar can be filtered using a windowed median filter.

H. Results Comparison

Table IV presents the statistical comparison of all experiments previously introduced. In experiments where multiple tests have been undertaken, the results are presented in the order of the appearance of its respective figures, from left to right, and separated by a ”–”.

TABLE IV
RESULT OF THE DIFFERENT EXPERIMENTS.

Experiment	HR Standard Deviation [bpm]	HR Mean Error [%]
A	N/A	N/A
B	N/A	5.61 — 19.7
C	9.25	6.7
D	8.64	12.54
E	9.81 — 5.5	8.49 — 6.73
F	2.25 — 2.87 — 6.43	1.94 — 3.42 — 5.92
G	2.37	1.99

By analyzing the results presented in Table IV, it is possible to confirm the observations done throughout the various experiments. It should be noted that since the radar takes about 10 to 15 seconds to get a valid reading, the data presented does not take into consideration any values until 15 seconds into the test. Although several experiments have been presented throughout this paper, an experiment that should be highlighted is Experiment G, since it demonstrates that the subject’s vital signs can be acquired at a distance of 1 meter.

V. Conclusion and Future Work

In this work, a low-cost COTS radar was evaluated to successfully obtain reliable subject’s vital signs around a distance of one meter. Various configurations of the radar operation for vital signs monitoring have been evaluated such as, distinct receiving gains, changing the number of transmitting antennas. Although good results were obtained, it should be noted that, depending on the tested subject, the heart rate could be fainter and the radar results might be unstable at 1 meter, limiting the maximum operating distance that can be used with this type of radar.

Since this is ongoing research, future work might include: i) testing people with different age intervals to see if there are implications since older people may have fainter vital signs; ii) testing people in different positions, mainly lying down in bed, since bed clothing not only attenuates more the signs, it might also create unwanted reflections; iii) improving the heart and breathing rate algorithms and the filters implemented can improve the obtained results, and finally iv) testing other radars at different frequency ranges, since lower frequencies have lower sensitivity which removes noise from small involuntary movement.

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