Vital signs monitoring with an FMCW MMwave radar sensor

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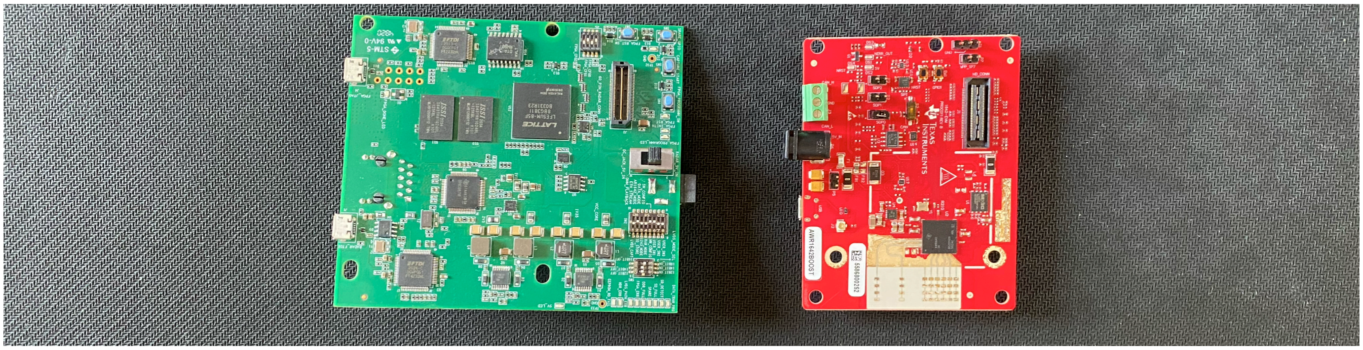

Fig. 1. The DCA1000EVM on the left and the AWR1642BOOST on the right

Abstract: In the medical sector sensors are used to measure vital sings like the heart rate and respiration rate. For the application of such sensors in the medical industry, movements of the heart and lungs must be detected with a high accuracy. An FMCW MMwave radar sensor can detect distance of objects with millimetre precision. Because the distance measurements can be done at a very high rate, small movements can be distinguished. Detection of small movements by a radar sensor can be helpful for certain medical applications where sensors cannot directly be attached to the skin. By measuring the movements of the thorax, vibrations of the heart and lungs can be detected from a distance. In this research a replication of the signal processing for detecting heart rate and respiration rate is investigated. Besides, research will be done on the reliability and accuracy of the collected data after processing. This to determine if the tested sensor is suitable for medical use.

Additional Key Words and Phrases: FMCW, MMwave, radar, heart rate, respiration rate, vital signs

1 INTRODUCTION

Measuring vital signs is important for medical purposes, currently the vital signs (respiration rate and heart rate) are measured by applying a stethoscope or sensor to the skin of a patient [8]. In some cases contact with the skin is unwanted for example when the patient has burns. In such cases remote measurement of these vital signs are of great importance. To measure vital signs remotely, radar sensors can be used. A radar transmits radio waves and receives the reflected wave. Since radio waves travel at the speed of light, the distance to an object or living being can be calculated. The higher the radar frequency, the smaller the range variations can be measured by the radar. An FMCW (Frequency Modulated Continuous Wave) radar increases the frequency linearly and repeats itself when the maximum frequency is reached. One sweep from the minimum to the maximum frequency is called a chirp [2]. MMwave (MilliMetre wave) indicates that the radar frequencies are between 30 and 300 GHz [5]. Because of this, FMCW MMwave radar sensors are able to make measurements in millimetre precision at a very high frequency. These specifications make it possible to detect tiny body movements. From the body movement data the respiration rate and heart rate can be deduced by use of signal processing [22]. Research has been conducted about measuring vital signs of multiple subjects at the same time [1, 3]. Developments like this can help speed up medical treatments and diagnoses.

The related articles studied during this research can be split into two groups. The first group is about how FMCW MMwave radar sensors work and how these can be used for several applications[14, 16]. The second group is about extracting the heart rate and respiration rate from the sensor data[2–4, 6, 17–20, 22, 24]. Even though the first group does not use the same sensor as used in this research, it gives information about how FMCW MMwave sensors work and how they can be used for certain measurements. The second group is directly related to this research. These articles include approaches on signal processing to extract heart rate and respiration rate information from the sensor data. The various signal processing steps used in these articles help to find the processing steps for extracting heart rate and respiration rate data. In the article of Pathipati Srihari, et al. [20] the exact same sensor is used as in this research. This article is very interesting as there is detailed information about the sensor settings that are used. Besides, there is information about how the data collected by the capture card can be processed. In the papers from Mostafa Alizadeh, et al. [4] and Kang Liu, et al. [17] two different approaches of signal processing are used for the FMCW MMwave radar sensor. The first signal processing step used in both researches is a range Fast Fourier Transform (FFT) to extract the occurring frequency from the radar output chirp. This data then is used to extract the distance of the target. After the distance calculation step, both researches make use of phase unwrapping to restore the phase signal. When the phase has been restored some steps follow to extract the heart rate and respiration rate. In the second research a band-pass filter is used where in the first research a vibration FFT is used to create a range vibration map.

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Vital sign measurement with an FMCW radar is a relative new development. To extract vital signs from the FMCW radar signal processing steps are needed. Several papers are available that use different signal processing steps, but often they show insufficiently detailed results and no comparisons with other methodologies. This study examines a number of signal processing steps described in the literature that are necessary to obtain accurate heart rate and respiration rate data. Where possible, the results from the processing steps are compared with each other. In addition, the final values for heart rate and respiration rate are compared with an independent reference measurement to gain insight into the accuracy of the investigated signal processing methods.

Based on the problem statement above, the following main research question is defined: Is it possible to measure the heart rate and the respiration rate (vital signs) of a human with an FMCW MMwave radar sensor? Additionally, the following sub questions will be investigated:

(1) Which radar parameters should be used for vital signs measurements?
(2) Which data processing steps are needed to collect vital signs data?
(3) How does distance influence the measurement of vital signs?
(4) How does the body position influence the measurement of vital signs?
(5) Is it possible to measure vital signs from multiple humans simultaneously

This research started with a literature study of articles that propose different signal processing steps based on raw data from an FMCW MMWave radar for extracting the heart rate and respiration rate. With the acquired knowledge about these signal processing steps, a number of methods are chosen and implemented in python [7] in the form of jupyter notebooks [15]. In addition, based, the configuration settings of the FMCW radar are determined by literature study. The signal processing steps cover the entire chain of steps required to extract the raw data, up to and including determination of the heart rate and respiration rate. After the signal processing steps have been implemented, the research focuses on the practical side of the use of radar sensor and data processing. By comparing the results of certain processing steps, the influence of these steps on the final heart rate and respiration rate is investigated. Besides, the influence of the distance between the radar and the human body is researched. In addition, an investigations are done regarding the influence of the body position and the ability of measuring multiple people simultaneously.

The structure of this paper is as follows. First, a global explanation is given about the working principle of an FMCW radar system. Next, the implemented signal processing methods are described, followed by an overview of the radar test setup used. Then a section is included regarding the test results followed up by a discussion. Finally, the paper will end with a conclusion.

2 MEASURING WITH AN FMCW RADAR

Detailed descriptions of the measuring principle of an FMCW radar can be found in various papers, like [2, 22], and in the manual [11] regarding the sensor. The FMCW radar used in this research sends out an outgoing chirp that starts at a frequency of 77 GHz and increases to a frequency of 81 GHz (TX chirp), see figure 2.The radar chirp reflects against the human body and is received by the radar(RX chirp) with a time delay (t_d). The radar system contains a frequency mixer module, which subtracts the frequencies of the TX chirp and RX chirp. In theory, this results in a pure frequency, the so-called Intermediate Frequency signal (IF signal). In practice, however, the pure IF frequency is disturbed by other unintended reflections that are received by the radar, but also, for example, by the electronics of the radar equipment itself. For any object in front of the radar, the frequency of the IF signal is a measure of the distance between radar and human body and can be easily calculated with the formula:

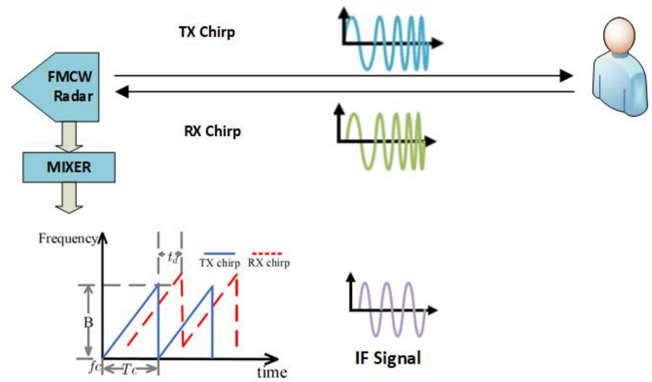

Fig. 2. Measuring principle of an FMCW radar

$$f = \frac{S2d}{c} \tag{1}$$

Here, f is the frequency of the IF signal in Hz, S is the rate at which the chirp frequency increases over time from the minimum set frequency to the maximum set frequency (typically in Mhz/μs), d is the distance between radar and object in m, and c is the speed of light in m/s. To measure vital signs, only determining the distance between FMCW radar and human body is not sufficient. For this it is necessary to measure tiny changes of the chest at the detected distance. This can be done by sending not one, but a series of chirps successively in a very short time. This is called a frame. By sending multiple frames it possible to compare the phase information of the associated frames, for example by taking the average values of the chirps sent and received. The phase angle of the outgoing TX chirps is known and can be compared with the phase angle of the associated incoming RX chirps, allowing the detection of very small changes in distance like respiration rate and heart rate.

3 PROCESSING STEPS

In this paper four different vital sign detection approaches are described. The first approach makes use of a Coarse To Fine (CTF) implementation which is initially proposed by Kang Liu, et al.[17]. The second approach makes use of an Ensemble Empirical Mode Decomposition (EEMD) [9]. The third implementations use a Discrete Wavelet Transform (DWT) [22] and the last approach uses a Butterworth band-pass filter to extract vital signs. An overview

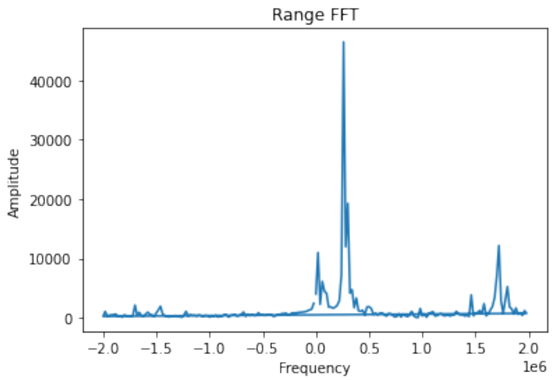

Fig. 3. Range FFT with a peak at 260 KHz using equation (1) a range of 0.56m is found

of the processing steps required to fulfill the aforementioned vital sign detection approaches are shown in figure 4 and are described in more detail below.

3.1 Range detection

The analog IF signal from the radar is converted into a digital signal by an Analog Digital Converter (ADC) for further signal processing. The first step for determining the vital signs is range detection. In this step a Fast Fourier Transform (FFT) is performed over the received IF signals. In the literature, this FFT is often referred to as the range FFT. The highest peak in the range FFT represents the most common frequency measured, see figure 3. This frequency is a measure of distance between the FMCW radar and the human, it can be calculated with equation (1). The distance calculated indicates the range at which the human is sitting.

3.2 Phase extraction

After range detection the IF signal belonging to the detected range can be used to extract phase information. Not all three detection approaches use the same method for this. In the CTF implementation the phase is directly extracted and unwrapped. In other words, the phase angle is calculated directly from the real and imaginary part of the selected range vectors using an inverse tangent. The result is a phase angle that is limited between 0 and 360 degrees. Larger angles are reduced by k x 360 degrees. This limitation is then corrected by unwrapping the phase. The EEMD implementation makes use of a so called phase accumulation methodology. In this approach, the radar transmits multiple frames, with each frame consisting of 32 chirps. In the EEMD implementation, the phase information of the 32 chirps within each frame are first accumulated and divided by 32. The result is an average phase angle per frame. This is where the name of phase accumulation comes from. Again, this step is followed by unwrapping the phase. In the DWT implementation the DC-offset will be corrected firstly. The DWT approach makes use of an extended Differentiate And Cross Multiply (DACM) algorithm [21] to extract the phase information. After, the differences between the phase angles are calculated. The band-pass filter approach uses the exact same phase differences as input.

3.3 Vital sign extraction

3.3.1 Coarse-to-Fine. The coarse to fine implementation makes use of a band-pass filters over the unwrapped phases. Two different band-pass filters are used. The first filter has a frequency range from 0.1 Hz to 0.9 Hz aiming to obtain the respiration rate. By applying an FFT over this filtered result and multiplying the frequency by 60 the respiration rate is determined. The second band-pass filter has a frequency range from 0.6 Hz to 4.2 Hz aiming to obtain the heart rate. A peak valley detection algorithm [17] is used on the result of this filter and the distance between the peak valley pairs is calculated. Peak valley pairs with a shorter distance than a certain threshold are removed. All peaks left over are counted and divided by the time, the result is a coarse estimation of the heart rate frequency. To determine a fine heart rate, the first or second peak is chosen depending on which frequency is closer to the coarse heart rate frequency. The fine heart rate can now be calculated by multiplying the frequency selected by 60.

3.3.2 EEMD. In the EEMD implementation the EEMD algorithm [9] is used on the phases and result in Intrinsic Mode Functions (IMF's). A FFT is done over each IMF to retrieve the maximum frequency occurring in the IMF. The average of all IMF's with a Peak frequency between 0.1 and 0.9 Hz is determined. A FFT over this results in the respiration rate frequency. The heart rate is calculated in a similar way only now if the peak frequency is between 0.8 and 3.0 Hz.

3.3.3 DWT and Band-Pass. The discrete wavelet transform implementation uses wavelets to filter the heart rate and respiration rate. The implementation in this research is a bit different than described in the DWT paper [22]. Instead of using a regular DWT, a Maximum Overlap Discrete Wavelet Transform (MODWT) is used. The benefit of using MODWT is that the number of data points used in the calculation is not halved in each decomposition step, all available information in the data set remains preserved throughout the decomposition. In this research the frame rate is 20 Hz as shown in table 1. Based on the Nyquist criterion this means that the maximum frequency that can be detected is 10 Hz. For detecting the frequencies for heart rate and respiration rate the relevant decomposition layers must be selected. For respiration rate the levels d5, d6 and d7 are selected and then reconstructed by an Inverse MODWT (IMODWT) function. The reconstruction of these layers results in a filtered dataset from 0.1 to 0.6 Hz. The heart rate is determined by levels d3 and d4 and the IMODWT function results in a filtered dataset from 0.6 Hz to 2.5 Hz. Over both filtered results an FFT is used to determine the most common frequency. The frequencies found are multiplied by 60 to retrieve the heart rate and respiration rate. Since the DWT works as a band-pass filter, alternative band-pass filters can be used instead of the DWT. An example of this is a Butterworth filter. In this research, a Butterworth filter has also been implemented as an alternative band-pass approach.

4 TEST SETUP

In this research an AWR1642BOOST radar sensor [12] from Texas Instruments is used. To capture the raw data from this sensor in addition a DCA1000EVM[13] is used. The sensor settings that are used in this research are described in table 1. For the measurement

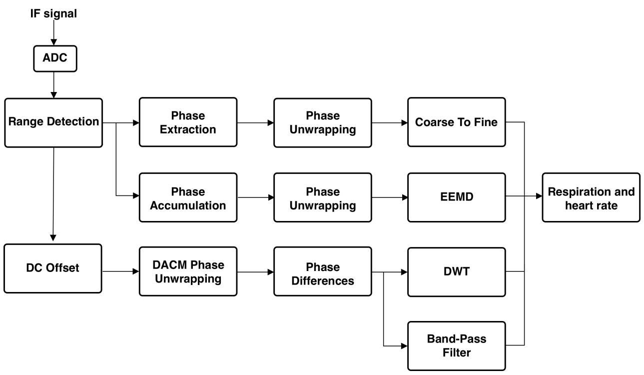

Fig. 4. Implemented signal processing steps and the relation between them

Table 1. Sensor Configuration

Parameter	Value	Unit
Start Frequency	77	GHz
ADC Samples	200	
ADC Start Time	5	μs
Samples Rate	4	Msps
Chirp Count	32	
Chirp Time	56	μs
Chirp Slope	70	MHz/μs
Bandwidth	3.92	Ghz
Frame Time	50	ms
Frame Rate	20	Hz
Frame Count	2400	
Tx Count	1	
Rx Count	1	

of the heart rate and respiration rate, the sensor is placed at chest height of the subject. The distance between the subject depends on the type of measurement. Measurements are done with distances ranging from 0.1 meter to 3 meter. As environment a room with minimal objects is chosen, The first objects in the Field Of View (FOV) are at a distance of 4 meters. In this research, the humans are sitting and do not move during a measurement. As reference sensor for the heart rate an Apple watch series 4 [10] is used. During the multiple people measurements also a Mi band 3 [23] is used as a heart rate reference sensor for the human that is sitting closest to the radar. To determine the respiration rate, the number of breaths is counted during the measurements and divided by the measurement time in minutes. The DCA1000EVM captures 2400 frames which means that every measurement has a total measurement time of 2 minutes.

5 RESULTS

In order to obtain better insight in the different measurement results of the four implemented approaches, the Mean Standard Deviation (MSD) is calculated on the obtained measurement results [22]. The MSD provides a measure of the mean spread of the obtained measurement results in relation to the mean reference values for respiration

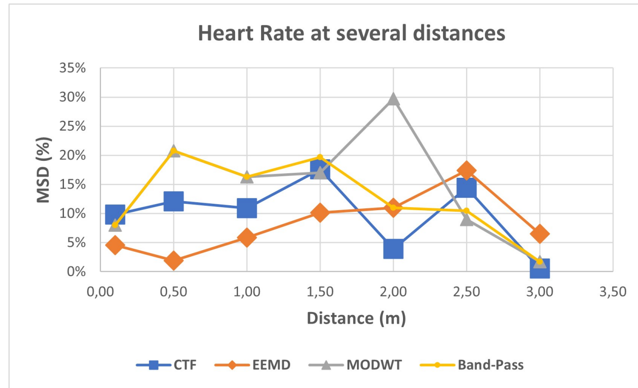

Fig. 5. Heart rate deviation at different distances

rate and heart rate.

$$\sigma = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(d-\bar{d})^2}}{\bar{r}} \tag{2}$$

In this calculation n is the amount of measurements per test, d is the difference between the reference value and the measured value. $\bar{d}$ is the mean difference of all measurements in a test and $\bar{r}$ is the average reference value over all measurements in a test. For every test and every method the MSD is calculated. The results are plotted in graphs with the mean standard deviation at the y axis and the test on the x axis. Each method has its own line in the graph.

5.1 Distances

To get information about the vital sign detection with an FMCW radar sensor at various distances, several measurements are performed. In total seven tests (0.1m, 0.5m, 1.5m ,2m, 2.5m, 3m) are done. For every distance, three measurements of two minutes have been performed on which the MSD is subsequently calculated. This results in two graphs, where figure 5 shows the heart rate deviation and figure 6 shows the respiration rate deviation. The figure concerning the respiration rate shows that the deviation in respiration relative to the average reference value is around 5% regardless of the signal processing method used and regardless of the measured distance. There is only an outlier for the MODWT at a distance of 1 meter. In the figure concerning the MSD for the heart rate at various distances, it is shown that the deviations depend on the method used and also depend on the distance. Compared to the other methods, the EEMD method seems to give a better result especially for short distances. For the band-pass filter this is the other way around. The CTF method gives a reasonably stable result regardless of the distance. The MODWT seems to get more accurate at greater distances. Also, it is notable that the deviations for the heart rate are significantly larger (roughly between 10% and 20%) than for the respiration rate.

5.2 Body positions

To investigate the influence of measuring vital signs of the human body in different positions, a separate test setup is created. The

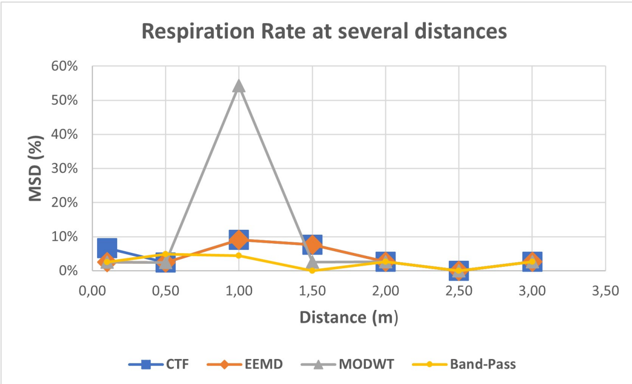

Fig. 6. Respiration rate deviation at different distances

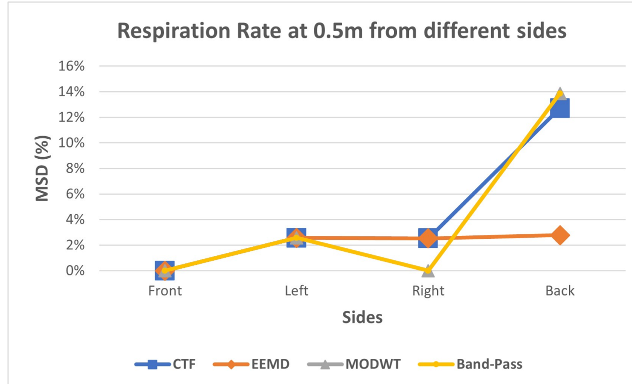

Fig. 8. Respiration rate deviation at different body angles

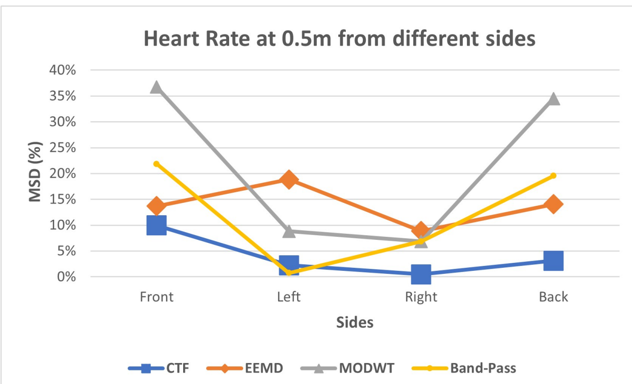

Fig. 7. Heart rate deviation at different body angles

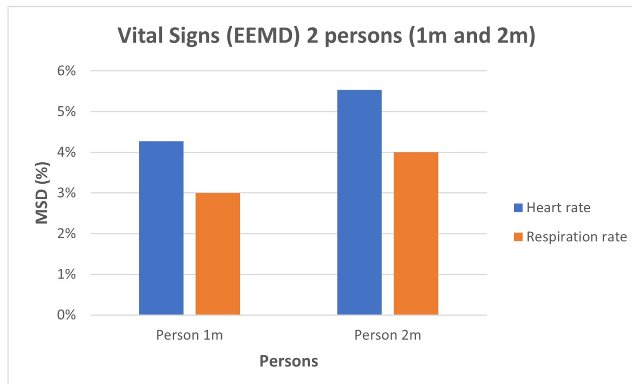

Fig. 9. Vital sign deviations for simultaneous measurement

distance from the person to the radar is 0.5 meter. Successively, four body positions are pointed to the radar, the front side, left side, right side and back side of a person. For each body position three measurements are performed. The results of the heart rate measurements are visible in figure 7. In this figure a parabola shape is presented for three of the four methods. This gives the impression that measuring human bodies from the left side and right side give better results. The CTF method seems less dependent on the measured body position. Contradicting, in figure 8 it is visible that the measurement of the respiration is best at the front side of the human body and less optimal at the back side.

5.3 Measuring multiple people

In total three measurements are performed with two persons in the field of view of the radar. One person is sitting in front of the sensor at a distance of two meters, where the other person is sitting at a small angle of 25 degree at a distance of one meter as visible in picture 10. This small angle is needed because otherwise the person sitting in front would block the radar signal for the person behind. Since the radar beam is cone shaped it is possible to measure at different angles from the radar. Because the two persons are sitting at different distances, their heart rate and respiration rate are located in different range bins and thus distinguishable. To find the correct peak for each person a search method is build in the code. Since the test setup is known the distance to each person is known as well. For every known distance a frequency range is created of half a meter before and half a meter after the distance. The highest peak is chosen in each range and will be processed with the EEMD approach to extract the vital signs. Because for each person the distance is calculated within a range of 1 meter it is of importance that the two persons have at least 1 meter distance between them. The results of measuring vital signs of multiple persons simultaneously are presented in figure 9. In this figure, it is visible that the heart rate and respiration rate of both persons can be determined with a rather low deviation. It is also visible that the person sitting at the greater distance of two meter has a bigger deviation than the person sitting close at one meter. Besides the Heart rates deviation is bigger in comparison to the respiration rate which is in line with the results of previous measurements.

6 DISCUSSION

In this research different processing methods are tested. The results of the respiration rate are very accurate across all four processing methods but the heart rate is less accurate than expected. If more

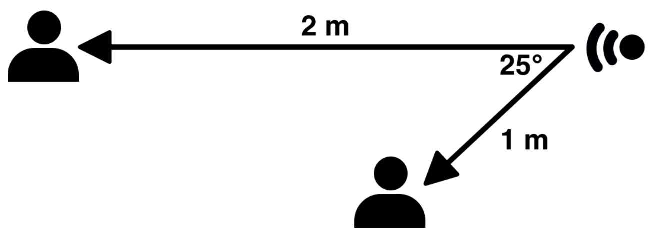

Fig. 10. Measuring setup for multiple people

time had been available for this project, quite a few things could be further investigated and improved. The EEMD implementation currently does not correct the DC-offset where Yaokun Hu and Takeshi Toda [9] propose to use a DC-offset. For further research the implementation of a DC-offset correction as part of the EEMD approach is advised. Currently, the sensor settings used are based on the literature study only. Further research may yield more optimal settings for measuring heart rate and respiration rate. It is proposed, for example, to measure with several transmitters and receivers simultaneously, with different transmitter-receiver pairs and possibly with different phase offsets. A disadvantage is that more data is generated, as a result more processing power is needed. All measurements are performed with the same limited number of test persons. To improve the research, more persons should be used with different genders, height, weight and age. This will make the results more reliable. Also, all tests in this research consist of only 3 measurements. As a consequence outliers have a big impact on the calculated deviations. Doing more measurements for each setting will strengthen the results. This especially is visible in the MODWT implementation which seems to be sensitive for outliers, both for respiration rate and heart rate measurements. In the paper describing the DWT method, it is proposed to use an additional rigrsure soft threshold method to filter out noise from the results after execution of the DWT. Implementing this step as well is advised and may solve the outliers in the results.

The captured results before and after DC-offset give a different result than described in the papers. The papers describe a clear circular spread in the data points. For the data captured in this research, a circular spread is shown but the center is filled with data points as well. An explanation for this might be the corrosion that is present on the antennas of the sensor. Since the heart rate consists of very small chest vibrations it is very sensitive to noise. The corrosion on the antennas may cause additional noise in the signal. Because of this, it would be a good idea to capture data with a different or new sensor preferably.

The reference devices used are an Apple Watch series 4 and a Mi Band 3. These devices only measure entire bpm cycles. Using a different heart rate reference device with a higher bpm accuracy will improve the results. The reference value for respiration rate were counted by the persons under test. The total respirations in the two minutes of measurement are divided by two, to determine the respiration rate. This method is prone to human error and is inaccurate as only entire respirations are counted. Using a reference device like an airflow sensor can determine the actual respiration rate more precise.

7 CONCLUSION

Based on this research it can be concluded that it is possible to measure vital signs of a human with an FMCW MMwave radar sensor. The sensor settings described in table 1 are able to measure raw data that contains information about heart rate and respiration rate. To extract the heart rate and respiration rate, signal processing steps are required. All tested signal processing methods contain similar steps. The first step is to determine the range bin with a range FFT. When the range bin is found, the phase is extracted and unwrapped for each frame. Subsequently, specific filtering is required for both heart rate and respiration rate frequencies. This can be done for example with an EEMD, DWT or Butterworth band-pass filter. The result of these methodologies consists of two datasets, one containing frequencies in the heart rate range and one containing frequencies in the respiration rate range. Finally, to determine the heart rate and respiration rate an FFT over both datasets must be performed. With these order of signal processing steps it is possible to collect vital signs data.

There is no obvious effect on the heart rate and respiration rate deviation in a range of 0.1 to 3 meter. More measurements and testing with greater distances will give more insight on this.

Measuring different sides of a human has influence on the deviation of the measured data. Heart rate measurement yields better results when measuring from the left side or right side. Respiration rate measurement yields the best result when the front side of the body is measured

It is possible to measure multiple people simultaneously when the humans are located at different distances. The distance between the humans must be big enough to be distinguishable by the range bin. The deviation for the person sitting further away is bigger for both heart rate and respiration rate.

In general, it is visible that the heart rate is less accurate than the respiration rate. This result was expected, as respiration results in bigger and slower movement of the chest in comparison with the very tiny movements for heart rate, which are very sensitive to noise.

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