Human Vital Signs Detection: A Concurrent Detection Approach

Tjahjo Adiprabowo 1,*, Ding-Bing Lin 1,*, Tse-Hsuan Wang 2,*, Ariana Tulus Purnomo 1, and Aloysius Adya Pramudita 3

1 Department of Electronic and Computer Engineering, National Taiwan University of Science and Technology, Taipei 10607, Taiwan; d10602808@mail.ntust.edu.tw
2 Pegatron, Taipei 11259, Taiwan; cfh120@hotmail.com
3 School of Electrical Engineering, Telkom University, Bandung 40257, Indonesia; pramuditaadya@telkomuniversity.ac.id
* Correspondence: d10602804@mail.ntust.edu.tw (T.A.); dblin@mail.ntust.edu.tw (D.-B.L.)

Abstract: The measurement of heartbeat rate and breathing rate for patients with sensitive skin, such as skin with burns, is very difficult to do, especially if the number of patients is large and medical personnel is limited. Therefore, this study seeks to propose a preliminary solution to this problem by proposing a device that can measure the vital signs of several people concurrently, especially the heartbeat rate and breathing rate, without attaching sensors to their skin. This is done using an FMCW (frequency-modulated continuous wave) radar that operates at 77–81 GHz. FMCW radar emits electromagnetic waves towards the chest of several targets and picks up the reflected waves. Then, using signal processing of these reflected waves, each target’s heartbeat rate and breathing rate can be obtained. Our experiment managed to perform concurrent detection for four targets. The experimental results are between 52 and 82 beats per minute for the heartbeat rates and between 10 and 35 breaths per minute for the breathing rates of four targets. These results are in accordance with normal heartbeat rate and normal breathing rate; thus, our research succeeded in proposing a preliminary solution to this problem.

Keywords: concurrent detection approach; frequency-modulated continuous wave radar; vital signs; signal processing

1. Introduction

This paper reports the research results on the detection of human vital signs using a frequency-modulated continuous-wave (FMCW) radar with a concurrent detection approach. Human vital signs, or briefly called vital signs, show the state of the important functions of the human body. There are several known vital signs [1]. The main ones are heartbeat rate, breathing rate, body temperature, and blood pressure. If a person’s vital signs are different from the normal values, then it is an early sign that this person is experiencing a health problem [2].

In this paper, only heartbeat rate and breathing rates are discussed. Henceforth in this paper, if we mention vital signs, we mean heartbeat rate and breathing rate.

Breathing rate and heartbeat rate are important vital signs that are considered in the medical field and observed as a physical indicator for many diagnosis activities. Most of the existing technologies, such as respiratory meters, spirometers, and photoplethysmography (PPG) that are employed to measure patient respiration, are operated as contact devices. For long-term monitoring purposes, contact devices exhibit the issues on the patient’s comfort and hygiene level. Moreover, respecting the COVID-19 virus spreading through direct contact, the use of contact devices will provide a higher risk than non-contact devices.

Radar technology has been studied to develop a non-contact device for human vital signs [3]. The multi-target detection capability is an important feature that needs to be developed for serving several patients with a minimum number of devices.
FMCW radar is a special type of radar that emits electromagnetic waves continuously, in the same manner as continuous-wave (CW) radar, except that FMCW radars can change their operating frequency during measurement. The basic features of the FMCW radar include: having the ability to measure tiny changes in the target distance with reference to the emitted wavelength; having the ability to measure the distance and speed of the target simultaneously; and very accurate distance measurement results [3].

In our research, the FMCW radar used is the TI IWR-1443, with an operational frequency of 77–81 GHz and a transmit power of 12 dBm [4]. The TI IWR-1443 is shown in Figure 1. In addition, as a comparison, this research also uses an oximeter.

Figure 1. The FMCW radar device used in this research.

In our experiments, this FMCW radar emitted electromagnetic waves to four targets. The receiving antenna on the FMCW radar received electromagnetic waves reflected by the four targets. The output signal of the receiving antenna was further processed using signal processing, which will be explained in the following sections, so as to produce the vital signs of the four targets. In addition, an oximeter was attached to a finger belonging to each target. This oximeter also shows the vital signs of each target.

Before we carried out this research, several researchers had already conducted similar experiments using the 77–81 GHz FMCW radar [5]. Still, the signal processing by these researchers was different from our signal processing. The authors of [5] used beam-forming weights to obtain the angular position of each target, whereas our method uses Two Dimensional Fast Fourier Transform (2D-FFT) to perform signal processing.

Another paper [6] also discusses the detection of human vital signs using the FMCW 76–81 GHz radar. The authors of the paper [6] detected vital signs on one person lying in a bedroom environment, while our experiment concurrently detected vital signs on four people in a sitting or standing position or lying down in any room environment.

The comparison of these experiments is shown in Table 1.
Table 1. Comparison with other works.

|                        | This Work | [5]  | [6]  |
|------------------------|-----------|------|------|
| Radar                  | FMCW      | FMCW | FMCW |
| Frequency              | 77–81 GHz | 77–81 GHz | 76–81 GHz |
| Multiple target separation | 2D-FFT       | Angular position (AoA) | X |
| Maximum Range          | 2.55 m    | 4.3 m | 2 m  |
| Concurrent Detection   | 4 people  | 2 people | 1 person |
| Experiment Environment | Indoor environment | - | Bedroom environment |

Thus, this method can help improve medical services [7] in measuring the vital signs of patients with sensitive skin, such as skin with burns, because the sensor is not attached to the body. Furthermore, this system can help overcome the limitations of medical personnel to serve many patients simultaneously in a little time because this system can detect the vital signs of four people at once.

In addition, the detection of human vital signs without physical contact can also be used in the process of rescuing people who were crushed by building debris due to earthquakes. This method can detect whether there are still survivors under the rubble of the building [8].

Thus, considerable benefits can be obtained from this human vital sign detection using a concurrent detection approach.

The next sections are summarized as follows: Section 2 explains the materials and methods, Section 3 provides the experimental results, Section 4 discusses the results, and Section 5 concludes the work.

2. Materials and Methods

2.1. Human Vital Signs

Vital signs need to be measured to determine a person’s level of health. Changes in the value of vital signs measurements can be a piece of early warning information about potential health problems. Under certain conditions, such as medical observation of a potentially serious disease or epidemic, it is necessary to measure vital signs continuously.

Normal vital signs vary with physiology, gender, age, exercise ability, weight, and overall health. The normal range of healthy vital signs for an inactive adult is:

- Breathing rate: 12 to 30 breaths per minute [9];
- Heartbeat rate: 60 to 100 beats per minute [10].

Even though a normal breathing rate is around 12 to 30 breaths per minute, some studies have concluded that a breathing rate as low as 8 breaths per minute is still in the normal category [11].

To detect vital signs, the radar must be able to detect movement in the chest caused by heartbeat and breathing. The heart is located in the rib cage inside the chest, as shown in Figure 2a. The heartbeat that pumps blood throughout the body triggers the heart wall to hit the chest wall so that the chest wall moves at the same rhythm as the heartbeat.
where $A$ is the amplitude; $f_c$ is the initial frequency; $B$ is the bandwidth; and $T$ is the period of time sweep.

This $s(t)$ signal is reflected back to the radar receiver by the target. The received signal $r(t)$ is the delay time $t_d$ version of the transmitted signal:

$$ r(t) = (A - \alpha) \cos(2\pi f_c(t - t_d) + \pi \frac{B}{T}(t - t_d)^2), $$

where $A$ is the amplitude; $\alpha$ is the path loss; $f_c$ is the initial frequency; $t_d$ is the time delay; $B$ is the bandwidth; and $T$ is the period of time sweep.

The received signal $r(t)$ is then further processed by the radar receiver system to produce a signal called beat signal $b(t)$. If there are four targets in the radar field of view, then the total beat signal is the sum of the four beat signals from each target. If known, $R_i$, $v_i$ is the velocity of the target $i$, and $\theta_i$ is the angle of arrival. Then, given $t_{is}$, $n$, and $k$, so the beat signal is as follows:

**Figure 2.** (a) The location of the heart in the rib cage inside the chest cavity [11]; (b) The location of the lungs inside the chest cavity [11].

The same phenomenon occurs in breathing. Breathing is the exchange of gases in the lungs. Air with carbon dioxide needs to be removed from the lungs, and air with oxygen needs to replace it.

The lungs are located in the chest cavity, as shown in Figure 2b. The movement of the lungs, expansion, and contraction when humans breathe causes the ribs to move. This movement of the ribs pushes the chest wall to also move up and down in the same rhythm as the movement of the lungs. Our research named this movement as chest displacement.

This chest displacement is detected by radar to produce heartbeat and breathing rate after signal processing.

### 2.2. Mathematical Formulation of the System

FMCW radar is a type of radar that emits a sinusoidal signal over a certain period of time sweep $T$. The sinusoidal signal is modulated by frequency modulation with a certain bandwidth $B$. This signal is also known as a chirp signal. A chirp signal is a sinusoidal wave whose frequency is increased linearly with time [12]. Its initial frequency is $f_c$.

The transmitted FMCW signal $s(t)$ is expressed as follows:

$$ s(t) = A \cos(2\pi f_c t + \pi \frac{B}{T}t^2). \tag{1} $$

where $A$ is the amplitude; $f_c$ is the initial frequency; $B$ is the bandwidth; and $T$ is the period of time sweep.

This $s(t)$ signal is reflected back to the radar receiver by the target. The received signal $r(t)$ is the delay time $t_d$ version of the transmitted signal:

$$ r(t) = (A - \alpha) \cos(2\pi f_c(t - t_d) + \pi \frac{B}{T}(t - t_d)^2), \tag{2} $$

where $A$ is the amplitude; $\alpha$ is the path loss; $f_c$ is the initial frequency; $t_d$ is the time delay; $B$ is the bandwidth; and $T$ is the period of time sweep.

The received signal $r(t)$ is then further processed by the radar receiver system to produce a signal called beat signal $b(t)$. If there are four targets in the radar field of view, then the total beat signal is the sum of the four beat signals from each target. If known, $R_i$, is the distance from the radar of the target $i$, $v_i$ is the velocity of the target $i$, and $\theta_i$ is the angle of arrival. Then, given $t_{is}$, $n$, and $k$, so the beat signal is as follows:
\[ b(t_s, n, k) \approx a \sum_{i=1}^{4} \left( \cos \left( 2\pi \left( \frac{B \cdot 2R_i}{T} t_s + \frac{2f_c v_i}{c} nT + \frac{d \sin(\theta_i)}{\lambda} k \right) \right) \right), \] (3)

where \( 0 < t_s < T \) is the number of Range Bins; \( 0 < n < (N - 1) \) is the number of Doppler Bins; and \( 0 < k < (K - 1) \) is the number of Virtual Antennas.

By obtaining the phases of the beat signals, the information about the relative distance between the target’s chest and the radar can be calculated. The distance is relative because the chest is constantly moving according to the rate of breathing and the rate of heartbeat.

2.3. Signal Processing Method

The sensor used in this study is a radar device that is installed at a certain distance from the person whose vital signs are being measured. Its illustration is shown in Figure 3.

![Illustration of a concurrent detection.](image)

This radar emits millimeter waves to the human body and, simultaneously, captures the waves reflected by the human body. These signals are used in further processing to generate heartbeat rate and breathing rate. The transmitting power of this radar is 12 dBm [4]. This concurrent, contactless measurement of vital signs makes measuring vital signs convenient for the patient and can be performed for long-term monitoring and home-based monitoring.

The system block diagram for the non-contact measurement of vital signs is shown in Figures 4 and 5. ADC is an analog to digital converter. The input to the ADC is a signal from the Low Pass Filter (LPF). The LPF is installed at the output of the mixer. The mixer and the LPF are inside of the TI IWR1443 [4]. The functional block diagram of TI IWR1443 is shown in Figure 6.
Figure 4. System block diagram up to Range Angle Map.

Figure 5. Block diagram of the system after Range Angle map [5].
Figure 6. The functional block diagram of TI IWR1443 [4].

To make it easier to understand, the signal processing will be explained with the signal originating from one antenna. The mixer mixes the signal called $r(t)$, originating from the receiving antenna Rx and the transmitted signal $s(t)$. The output of the LPF is called the beat signal $b(t)$.

The beat signal can be formulated mathematically using Equations (1) and (2) as follows:

$$b(t) = \text{LPF}(s(t)r(t)) = \frac{\alpha}{2} \cos \left( 2\pi B t_d + 2\pi f c t_d - \pi B t_d^2 \right). \quad (4)$$

Let $t_d = \frac{2R}{c}$, $f_c = \frac{c}{\lambda}$, and ignore small values, then $b(t)$ becomes:

$$b(t) \approx \frac{\alpha}{2} \cos \left( 2\pi \frac{B}{T} \frac{2R}{c} t + 4\pi \frac{R}{\lambda} \right) = \frac{\alpha}{2} \cos(2\pi f_b t + \phi_b), \quad (5)$$

where $f_b$ is the frequency of the beat signal; and $\phi_b$ is the phase of the beat signal.

The first Fast Fourier Transform (FFT) operation to the ADC output produces the frequency and phase of the beat signal. The range $R$ can be calculated from these quantities using the following formulas:

$$f_b = \frac{B}{T} \frac{2R}{c}, \quad (6)$$

$$\phi_b = \frac{4\pi R}{\lambda}. \quad (7)$$

The system uses four receiver antennas and two transmitter antennas. The transmitter antennas operate in alternate mode, so eight receiving antenna signals are received from Rx1 to Rx8.

The second FFT is performed to the range data of each range. As there are 8 Rx signals, the 2D-FFT will produce peaks [13] in the same location but with different phases. The measured phase difference $(\delta)$ can be utilized to calculate the angle of arrival $(\theta)$ of the target [14]. It is mathematically written as follows:

$$\delta = \frac{2\pi d \sin(\theta)}{\lambda} \rightarrow \theta = \sin^{-1} \left( \frac{\lambda \delta}{2\pi d} \right), \quad (8)$$
where \( d \) is the distance between adjacent Rx antennas.

Therefore, this process produces range angle data. Then, it is packed into one map called Range Angle Map.

The static data is removed from the data in the Range Angle Map by differential processing because only dynamic data, which comes from chest displacement, is needed for the next process. Other slow-large-scale human random body movements (RBM) \[15,16\] can be considered as static data when compared to chest displacement due to breathing and heartbeat rates.

Clutters \[17\] in environments can also be considered as static data, and their influences can be canceled using this differential processing.

Subsequently, the smoothing process is carried out to prepare the data in Range Angle Map for further processing to produce vital signs.

Then the Phase Unwrapping \[18\] process is carried out to solve the ambiguity of the phase. This Phase Unwrapping process is carried out in phases so that the resulting phases range between \(-\pi\) and \(+\pi\), i.e., phases that reflect the actual chest displacements \[19\]. The results of this Phase Unwrapping process are displayed in the image of the measurement result with the name Chest Displacement.

Then the next process is the Phase Differences. Phase Differences are conducted by subtracting the results of sequential unwrapped phases. The goal is to obtain a strong heartbeat signal and to eliminate phase shift.

Next is Impulse Noise Removal. The Phase Unwrapping process may cause this impulse-shaped noise. After this, filtering is conducted to obtain breathing and heartbeat data.

Breathing data is obtained as the output of the Band Pass Filter with a passband of 0.1–0.5 Hz. At the same time, the heartbeat data is obtained as the output of the Band Pass Filter with a passband of 0.8–4.0 Hz. The output of these two BPFs is shown as Breathing Waveform and Heart Waveform in the measurement picture.

Breathing BPF output is directly entered into the Rate Estimation stage, while the heartbeat BPF output is first passed through the Motion Corrupted Segment removal. This process aims to reduce the effect of amplitude movements that are too large in the heartbeat estimation. If the energy of the data segment is less than the specified energy limit \((E < E_{Th})\), the data segment is continued to the buffer to be processed at Rate Estimation. If the energy of the data segment is greater than the specified energy limit \((E > E_{Th})\), the data segment is discarded.

In the Rate Estimation, three processes are carried out: FFT, autocorrelation, and estimation of vital signs based on the distance between peaks (Peak Interval) in the waveform in the time domain.

FFT needs to be implemented to obtain spectral information \(x(t)\) from the breathing waveform and heartbeat waveform.

This spectral information \(x(t)\) contains peak values \[20\] with positions that are at a certain distance from one another. This distance is referred to as Peak Interval. These peak values are the harmonics of the fundamental frequency. The fundamental frequency’s period is the distance between peaks. Auto-correlation \[21\] is required to identify a fundamental frequency in this spectral information \(x(t)\).

Furthermore, as the final stage, vital sign decisions are carried out based on confidence metrics \[5\] both for breathing and for heartbeat so that the resulting breathing rate and heartbeat rate are generated.

The experiment used four types of programming software to conduct signal processing.

The first is Cython \[22\] programming software. Here we write a source code file with extension pyx. We call it the pyx file, as shown in Figure 7. Then from the file, cython generates a C Extension File, which we call c file.
The first is Cython [22] programming software. Here we write a source code file with extension pyx. We call it the pyx file, as shown in Figure 7. Then from the file, cython generates a C Extension File, which we call c file.

This C programming is chosen because its running time is the fastest among other programming languages. This C file also contains source code in Python. The C compiler then compiles this c file to become a Python Extension Module [23] with extension pyd, which we call a pyd file.

The .pyd file also includes library files. The library files are *.h files and *.c files. The .pyd file can be imported directly by the Python source code.

Then along with PyQt [24], the Python source code is assembled to produce images and numbers of heartbeat rates and breathing rates in the form of a Graphical User Interface (GUI) on a computer screen [25].

3. Results

In our experiment, the multiple vital signs concurrent detection was carried out to several people simultaneously using one radar device. The radar device was mounted at a certain distance from people whose vital signs were being measured. The radar transmitted millimeter waves to several people at once, and then the radar captured the waves reflected from each person.

The reflected waves captured by the radar were then processed in signal processing as described in Section 2 to produce the heartbeat rate and breathing rate of several people at once. The radar then showed each person’s heartbeat rate, breathing rate, heartbeat waveforms, breathing waveform, chest displacement waveforms, and range angle graph on a computer monitor screen.

The results of the vital signs measurement are shown in Figures 8–12. There are several quantities demonstrated in these pictures. First is the Range Angle Map. Next is the Chest Displacement chart. Then the Breathing Waveform graph is also shown. Next, the Heart Waveform graph is displayed. All of the graphs show the results of the multiple concurrent vital sign measurements for four targeted people.
Figure 8. Data 1.

Figure 9. Data 2.

Figure 10. Data 3.
Besides that, the breathing rates and heartbeat rates of the four people being targeted are also shown in the form of numbers simultaneously, so that the users can directly read it. In that display of numbers, these measurement results of rates are referred to as vitalSigns_1, vitalSigns_2, vitalSigns_3, and vitalSigns_4.

The results of the vital signs measurement by the oximeter as a comparison are shown in Figure 13a–d and written in Table 2 as follows:

**Table 2. Oximeter measurement results.**

| Target 1 | Target 2 | Target 3 | Target 4 |
|----------|----------|----------|----------|
| Heartbeat rate | 69 | 80 | 69 | 75 |
| Breathing rate | 10 | 21 | 16 | 21 |

**4. Discussion**

The experiment succeeded in conducting the concurrent detection of the vital signs of four people. The results of measuring the vital sign of each target do not affect each other.
Besides that, the breathing rates and heartbeat rates of the four people being targeted are also shown in the form of numbers simultaneously, so that the users can directly read it. In that display of numbers, these measurement results of rates are referred to as vitalSigns_1, vitalSigns_2, vitalSigns_3, and vitalSigns_4.

The results of the vital signs measurement by the oximeter as a comparison are shown in Figure 13a–d and written in Table 2 as follows:

![Figure 13. (a) Target 1; (b) Target 2; (c) Target 3; (d) Target 4.](image)

|                | Target 1 | Target 2 | Target 3 | Target 4 |
|----------------|----------|----------|----------|----------|
| Heartbeat rate | 69       | 80       | 69       | 75       |
| Breathing rate | 10       | 21       | 16       | 21       |

**4. Discussion**

The experiment succeeded in conducting the concurrent detection of the vital signs of four people. The results of measuring the vital sign of each target do not affect each other.

Factors that should be considered are as follows: the distance between targets and radar should not exceed 2.55 m; any objects should not block the space between the targets and the radar.

The power transmitted by the radar is safe for humans because it is 12 dBm or around 15.8 mW. Its power density is lower than the Maximum Permissible Exposure (MPE) recommended by the Institute of Electrical and Electronics Engineers (IEEE) [26].

The factor of the radar’s antenna that can be considered is its parameters including its directivity. Directivity is a measurement of the capability of an antenna to focus radiated power in a certain direction. It is corresponded to the radiation intensity. The directivity of an antenna is the ratio of the attained radiation intensity in a certain direction to that of an isotropic antenna. In reality, someone is usually more interested in the peak directivity of the main lobe. Gain of an antenna equals to directivity of the antenna multiplied by radiation efficiency [27].

The antenna configuration of TI-IWR1443 consists of 3 Tx (transmitter) antennas and 4 Rx (Receiver) antennas. In our design, only 2 Tx antennas and 4 Rx antennas are used. Because the transmitter antennas operate in alternate mode, there are 8 signals received, namely from Rx1 to Rx8.

According to the TI-IWR1443 User’s Guide, the antenna peak gain of TI-IWR1443 is \(>10.5 \text{ dBi}\) across the frequency band of 76 to 81 GHz; the horizontal 3dB-beamwidth is approximately \(\pm 28\) degrees, and elevation 3dB-beamwidth is approximately \(\pm 14\) degrees; the horizontal 6dB-beamwidth is approximately \(\pm 50\) degrees, and the elevation 6dB-beamwidth is approximately \(\pm 20\) degrees [28].

Thus, these antenna parameters are sufficient to support measurements of four objects at once.

There are three methods used to display the data of measurement results, namely: mapping the distance and angle of each target from the radar; the waveform appearance
of the chest displacement, heartbeat and breathing of each target; and the numerical appearance of all targets.

From the range angle map, we can see the data as follows: the distance of each target from the radar; the heartbeat rate of each target; the breathing rate of each target; and the identification of the target sequence number according to the data shown by the numeric display. Likewise, the angle of the position of each target in the room can be seen.

The distance of each target or objects can be identified because their reflected signals produce different beat signals. The distance or range of each target can be derived from the frequency and phase of these beat signals. Figure 14 clarifies the concept [29].

![Beat frequency spectrum in FMCW radar](image)

Figure 14. Beat frequency spectrum in FMCW radar [29].

It can also be said that the range angle map shows several strong signatures that indicate the target positions. The target positions are determined by the combination of range and angle data. The range data are obtained from the beat frequency, and the angle data are obtained by exploiting the feature of the IWR 1443 FMCW module. The result in range angle map indicates that four targets are located as \((r_1, \theta_1), (r_2, \theta_2), (r_3, \theta_3),\) and \((r_4, \theta_4)\). We can see in these maps that the locations of the four objects are the same.

The target positions shown on this range angle map is not the actual position of the targets because this map is a mapping of the actual target positions to a map where the vertical axis is the distance from the radar to each target and the horizontal axis is the angle of the position of each target to the radar.

The chest displacement, heartbeat, and breathing waveform graphs in Figures 8–12 are obtained from the chest wall displacement detection. The vertical axis unit of these figures is mm, and the horizontal axis of these figures is Frame Index. The A-frame consists of a sequence of chirps [30], as shown in Figure 15.

![FMCW chirp and frame structure](image)

Figure 15. FMCW chirp and frame structure [30].
We can see that the chest displacement signals are more complex than the heartbeat and breathing signals graphs. The reason for this is that the chest displacement signal is still a summation of heartbeat and breathing signals. On the other hand, heartbeat and breathing signals look simpler. Likewise, we see that the heartbeat signal is of a higher frequency than the breathing signal. This corresponds to the fact that the heart rate is faster than the breathing rate. In these figures we can also indicate the intervals between respiratory and cardiac activities.

In the numerical display, we can see the heartbeat rate of each target, the breathing rate of each target, the distance and angle of position of each target from the measurement site. The target distances of 1 to 4 successively from the radar are as follows: 0.82 m, 1.11 m, 0.62 m, and 1.11 m. The angles of the target positions 1 to 4 from the radar are shown in degree: −18, 18, 22, and 37. A minus angle means that the target is to the left of the radar, while a positive angle implies that the target is to the right of the radar.

We can also attain the results of the spectral estimation method reported as pk, FT, and CM. The pk stands for peak interval. What is meant by FT is FFT (Fast Fourier Transform). CM stands for confidence metric. These entities are explained in Section 2. The peak interval is the distance between peak values in the spectral information. These peak values are the harmonics of the fundamental frequency. The process of FFT is needed to obtain the spectral information of the heartbeat waveforms and breathing waveforms [31], while the confidence metric is the last step to decide the values of the recorded heartbeat rates and breathing rates.

The results of heartbeat rate measurements are shown by the numbers at the upper parts of vitalSigns_1 to vitalSigns_4. These are between 52 and 82 beats per minute. These heartbeat rate measurement results correspond to normal heartbeat rates, as shown in Section 2. This proves that the method used in our experiments for heartbeat rate measurements is correct because the results are in accordance with the normal heartbeat rates of healthy people.

The results of breathing rate measurements are shown by the numbers at the lower parts of vitalSigns_1 to vitalSigns_4. They are between 10 and 35 breaths per minute. These breathing rate measurement results correspond to normal breathing rates, as shown in Section 2; therefore, this proves that the method used in our experiment for breathing rate measurement is also correct.

It can be seen that there are data match between the measurement data from the range angle map image and the numerical measurement results.

The results of vital sign measurements by this radar were also compared with the results of vital sign measurements by oximeter. From the measurement of vital signs using an oximeter, the obtained heartbeat rate results were between 69 and 80 beats per minute, and breathing rates were between 10 and 21 breaths per minute. We can see here that the measurement of vital signs using these two different measuring instruments produce similar data.

5. Conclusions

The motivation of this research was to identify effective strategies for dealing with the measurement of heartbeat rate and breathing rate for patients with sensitive skin, such as skin with burns, especially if the number of patients is large and medical personnel is limited. Our experiment solved this problem by measuring the vital signs of four targets at once using an FMCW radar with a frequency of 77–81 GHz as a remote sensor. We then processed the data using signal processing so that it produced a display of vital sign measurement results. Based on the results of our experiment and explanation, as reported in this paper, it can be concluded that it is possible to measure the vital signs of several people at once without attaching sensors to these people. In other words, the measurement uses a concurrent detection approach. For future development, the method used in our experiment can be categorized as a first step to be further developed for use in the medical world and in the area of Search and Rescue.
Author Contributions: Conceptualization and methodology, T.A. and T.-H.W.; software, T.A. and T.-H.W.; validation, T.A. and T.-H.W.; formal analysis, T.A., D.-B.L. and T.-H.W.; resources, T.A., D.-B.L. and T.-H.W.; data, T.A., D.-B.L. and T.-H.W.; writing—original draft preparation, T.A.; writing—review and editing, T.A., D.-B.L., T.-H.W., A.T.P. and A.A.P.; visualization, T.A. and A.T.P.; supervision, D.-B.L., T.-H.W. and A.A.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Ministry of Science and Technology of Taiwan under Grant MOST 110-2221-E-011-052.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lv, W.; He, W.; Lin, X.; Miao, J. Non-Contact Monitoring of Human Vital Signs Using FMCW Millimeter Wave Radar in the 120 GHz Band. Sensors 2021, 21, 2732. [CrossRef] [PubMed]
2. Yang, X.; Zhang, X.; Ding, Y.; Zhang, L. Indoor Activity and Vital Sign Monitoring for Moving People with Multiple Radar Data Fusion. Remote Sens. 2021, 13, 3791. [CrossRef]
3. Sacco, G.; Puzzi, E.; Pizzella, E.; Pisa, S. An FMCW Radar for Localization and Vital Signs Measurement for Different Chest Orientations. Sensors 2020, 20, 3489. [CrossRef] [PubMed]
4. Texas Instruments. Available online: http://www.ti.com/lit/ds/symlink/iwr1443.pdf (accessed on 12 October 2021).
5. Ahmad, A.; Roh, J.C.; Wang, D.; Dubey, A. Vital Signs Monitoring of Multiple People using a FMCW Millimeter-Wave Sensor. In Proceedings of the 2018 IEEE Radar Conference, Oklahoma City, OK, USA, 23–27 April 2018; IEEE: Piscataway, NJ, USA, 2018. [CrossRef]
6. Alizadeh, M.; Shaker, G.; Almeida, J.C.M.D.; Morita, P.P.; Naeini, S.S. Remote Monitoring of Human Vital Signs Using mm-Wave FMCW Radar. IEEE Access 2019, 7, 54958–54968. [CrossRef]
7. Yuan, Y.; Lu, C.; Chen, A.Y.K.; Tseng, C.H.; Wu, C.T.M. Noncontact Multi-Target Vital Sign Detection using Self-Injection-Locked Radar Sensor based on Metamaterial Leaky Wave Antenna. In Proceedings of the 2019 IEEE MTT-S International Microwave Symposium, Boston, MA, USA, 2–7 June 2019. [CrossRef]
8. Liu, L.; Liu, S. Remote Detection of Human Vital Sign with Stepped-Frequency Continuous Wave Radar. IEEE JSTARS 2014, 7, 775–782. [CrossRef]
9. Medscape. Available online: https://emedicine.medscape.com/article/2172054-overview#a3 (accessed on 12 October 2021).
10. UpBeat. Available online: https://upbeat.org/early-warning-signs/slow-heartbeat (accessed on 12 October 2021).
11. Droitcour, A.D. Non-Contact Measurement of Heart and Respiration Rates with Single-Chip Microwave Doppler Radar. Ph.D. Thesis, Stanford University, Stanford, CA, USA, 2006.
12. Brooker, G.M. Understanding Millimetre Wave FMCW Radars. In Proceedings of the 1st International Conference on Sensing Technology, Palmerston North, New Zealand, 21–23 November 2005.
13. Su, L.; Wu, H.S.; Tzuan, C.K.C. 2-D FFT and time-frequency analysis techniques for multi-target recognition of FMCW radar signal. In Proceedings of the Asia-Pacific Microwave Conference 2011, Melbourne, Australia, 5–8 December 2011.
14. Introduction to Mmwave Sensing: FMCW Radars. Available online: https://training.ti.com/sites/default/files/docs/mmwaveSensing-FMCW-offlineviewing_0.pdf (accessed on 12 October 2021).
15. Lv, Q.; Chen, L.; An, K.; Wang, J.; Li, H.; Ye, D.; Huangfu, J.; Li, C.; Ran, L. Doppler Vital Signs Detection in the Presence of Large-Scale Random Body Movements. IEEE TMTT 2018, 66, 4261–4270. [CrossRef]
16. Tu, J.; Hwang, T.; Lin, J. Respiration Rate Measurement Under 1-D Body Motion Using Single Continuous-Wave Doppler Radar Vital Sign Detection System. IEEE TMTT 2016, 64, 1937–1946. [CrossRef]
17. Chang, W.F.; Chen, K.W.; Yang, C.L. Noise Tolerable Vital Sign Detection Using Phase Accumulated Demodulation for FMCW Radar System. In Proceedings of the 2018 IEEE International Microwave Biomedical Conference, Philadelphia, PA, USA, 14–15 June 2018. [CrossRef]
18. Guoqing, Q. High accuracy range estimation of FMCW level radar based on the phase of the zero-padded FFT. In Proceedings of the 7th International Conference on Signal Processing, Beijing, China, 31 August–4 September 2004. [CrossRef]
19. Texas Instruments. Driver Vital Signs—Developer’s Guide; Texas Instruments: Dallas, TX, USA, 2017; pp. 1–30.
20. Wang, S.; Pohl, A.; Jaeschke, T.; Czaplik, M.; Kony, M.; Leonhardt, S.; Pohl, N. A Novel Ultra-Wideband 80 GHz FMCW Radar System for Contactless Monitoring of Vital Signs. In Proceedings of the 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Milan, Italy, 25–29 August 2015. [CrossRef]
21. Svensson, J. High Resolution Frequency Estimation in an FMCW Radar Application. Master’s Thesis, Linköping University, Linköping, Sweden, 2018.
22. Cython. Available online: https://cython.readthedocs.io/en/latest/src/tutorial/cython_tutorial.html (accessed on 12 October 2021).
23. Python. Available online: https://docs.python.org/3/extending/building.html (accessed on 12 October 2021).
24. Tutorialspoint. Available online: https://www.tutorialspoint.com/pyqt/index.htm (accessed on 12 October 2021).
25. Computer Hope. Available online: https://www.computerhope.com/jargon/g/gui.htm (accessed on 12 October 2021).
26. C95.1 Edition-1999—IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz. Available online: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=757105 (accessed on 12 October 2021). [CrossRef]
27. Johnson, R.C. Antenna Engineering Handbook, 3rd ed.; McGraw-Hill, Inc.: Atlanta, GA, USA, 1993; pp. 1.4–1.5.
28. Texas Instruments IWR1443BOOST User Manual. Available online: https://www.manuallib.com/manual/1976384/Texas-Instruments-Iwr1443boost.html (accessed on 10 November 2021).
29. Using a Complex-Baseband Architecture in FMCW Radar Systems. Available online: https://www.ti.com/lit/pdf/spyy007 (accessed on 12 October 2021).
30. Machado, S.; Mancheno, S. Automotive FMCW Radar Development and Verification Methods. Master’s thesis, Chalmers University of Technology, University of Gothenburg, Gothenburg, Sweden, 2018.
31. Purnomo, A.T.; Lin, D.B.; Adiprabowo, T.; Hendria, W.F. Non-Contact Monitoring and Classification of Breathing Pattern for the Supervision of People Infected by COVID-19. Sensors 2021, 21, 3172. [CrossRef] [PubMed]