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A Review of Contactless Vital Signs Monitoring Technology Based on Millimeter-Wave Radar

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Abstract

Non-invasive vital sign surveillance has garnered significant focus across sectors like intelligent medical care, wellness tracking, and crisis management because of its superior comfort and persistent surveillance features. Millimeter-wave radar, characterized by its high sensitivity to subtle human motion, robust environmental adaptability, and confidentiality preservation, has emerged as a vital technical pathway for non-contact physiological monitoring. This article examines the current evolution of millimeter-wave radar-driven vital-sign detection systems, provides a comprehensive summary of its fundamental sensing mechanisms, and presents a thorough evaluation of the critical technologies for monitoring multiple individuals simultaneously. Based on contemporary investigations, it integrates and scrutinizes the core ideas, practical contexts, and attributes of representative approaches—such as range partitioning, positional partitioning, signal separation, and deep learning—and highlights the trajectory in multi-person vital sign tracking toward intelligent processing, shifting away from mechanical isolation. Concurrently, the study addresses obstacles encountered in regions, such as target discrimination in intricate settings, algorithm stability, data availability, and practical implementations, and clarifies future paths for advancement. This research could function as a guide for investigating and utilizing millimeter-wave radar-enabled non-contact vital-sign tracking technology.

Keywords

millimeter-wave radar, non-contact vital sign monitoring, multi-person detection, signal separation, FMCW radar

1. Introduction

1.1 Background

Vital signs provide a first glimpse into the physiological condition of a human being, and the respiratory and heart rates are the primary indicators of life and have become part of current clinical practice, general health surveys, and acute medical interventions. Currently, the monitoring of vital signs has largely relied on physical methods, using tools such as an electrocardiogram (ECG), a pulse oximeter worn on a finger, or a chest belt to obtain information. These tools are usually quite accurate but have certain limitations. A few of the devices are bulky to wear and unsuitable for long-term use; repeated applications of the conductive gel used in ECG monitoring can cause skin irritation or allergic reactions. Furthermore, certain contact-based

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devices are still out of reach for the average person; hence, their use in household, chronic, or population-based monitoring is limited [1].

Due to the limitations of contact-dependent tracking, studies have recently shifted into non-contact physiological sign monitoring. Methods based on optical cameras or audio sensing devices can be effective for remote quantification. Still, the real-world application is limited by issues such as lighting, interference, and confidentiality concerns and hence cannot guarantee long-term, dependable performance [2]. In contrast with the above-mentioned methods, millimeter-wave radar emits electromagnetic waves upon an object. Then it receives the reflected echoes, enabling it to detect extremely small thoracic vibrations caused by breathing or a heartbeat, thereby enabling contactless detection. The high accuracy of millimeter-wave radar, its sensitivity to change, and the fact that it does not image are making it an area of growing interest in the research on non-contact vital-signs monitoring [3].

Regarding the equipment and signal processing used in millimeter-wave radar, there was much academic research in the past focused on elementary detection of either an individual's breathing or heart rate; recently, discussions have shifted towards more complex scenarios such as sleep stages, body posture, and the vital signs of multiple individuals. However, when tracking numerous people, the recorded breath and heart echoes often overlap, making it challenging to separate each person's signals [4]. There can be an assertion that the challenge of providing long-term, steady operation of multi-person vital sign monitoring in practical applications is still critical and needs to be overcome.

1.2 Research Objective

This work will provide an in-depth summary of non-invasive methods for monitoring vital signs using millimeter-wave radar, with a particular focus on studies of multi-occupant vital-sign identification. There are two major areas of investigation. First, the basic mechanisms and key elements of signal analysis for detecting vital signs using millimeter-wave radar. Second, various methods developed to support multi-person situations and their evolutionary lines.

2. Theoretical Framework

2.1 Basic Model of FMCW Radar

Major methods of vital-sign monitoring used in millimeter-wave radar systems typically rely on the fundamentals of frequency-modulated continuous-wave (FMCW) radar. In FMCW designs, the emitted electromagnetic pulses are linearly frequency-modulated over time. When they encounter a human body, reflected echoes are formed and then gathered by the radar in the direction of the target. As there is a fixed time gap between the emission and reception of these waves, the waveforms are mixed to produce an intermediate frequency (IF) signal that accurately indicates where the target is and how it moves relative to the receiver [5].

When detecting things in practice, the radar first performs a range-direction fast Fourier transform (Range FFT) on the received intermediate-frequency data to determine the target distribution on the range axis. If there is a human form located in the observed area, the particular range cell where it is present can be identified by the corresponding peak in the range spectrum. At that point, the phase of this particular cell is recorded to serve as a basis for subsequent studies of vital signs (i.e., information about movement or respiration) [1].

Consequently, in terms of signal analysis, applying FMCW radar to measure physiology requires first resolving the target-range issue, i.e., determining the location of the human participant, and then extracting information about the thorax's movement from the returned echoes received at that location.

2.2 The Relationship Between Minor Displacements in the Thoracic Cavity and Phase Changes

Breathing and heart action cause small, regular distortions in the thoracic area. Even though these fluctuations are very small, millimeter-wave radar, operating at relatively low frequencies, can still detect changes on the order of millimeters. Assuming that the thoracic region moves slightly in the anterior-posterior

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direction, the path of the reflected pulse detected by the radar changes, as well as the phase of the pulse changes accordingly.

On average, the difference in volumes between the thorax cavity is associated with the duration of the radar signal as follows:

$$\phi(t) = \frac{4\pi x(t)}{\lambda} \tag{1}$$

In this context, $\phi(t)$ represents the phase change experienced by the echo, $x(t)$ denotes the displacement of the thoracic cavity, and λ is the wavelength of the radar wave. The relationship presented in this paper directly reflects the relationship between the displacement of the thoracic cavity and the phase of the echo. It follows that if a phase sequence (i.e., a series of phase values) related to the target distance can be accurately obtained, it is possible to use it to assess the status and characteristics of respiration or heartbeat.

It is important to distinguish between respiratory and cardiac signals as follows: the first is characterized by high amplitude and low frequency, and the second by low amplitude and high frequency. Based on these characteristics, the authentic heart rate data obtained are extremely susceptible to interference from breathing, light physical movements, and ambient sound; eliminating such interference is one of the main challenges to overcome in subsequent steps.

2.3 Vital Signs Signal Processing Workflow

After obtaining phase data related to a human subject, further processing is necessary to extract respiratory and cardiac rates. The process of millimeter-wave radar dealing with vital signs should be performed progressively by using phase demodulation, phase unwrapping, filtering and spectral analysis, as it was done traditionally.

The initial step in the framework involves identifying the phase sequences based on distance intervals at which human subjects are placed. The cyclic changes in the radar-received phase information should be analyzed, and phase extension methods are used to obtain a continuous image of the phase evolution. Then appropriate filters are constructed depending on the frequency bands of the breathing or cardiac signals. In the human body, the ventilation frequency typically varies between 0.1 and 0.5 Hz (or 6-30 breaths per minute), as opposed to the heartbeat frequency, which typically ranges between 1 and 2 Hz (or 60-120 pulses per minute). With this in mind, bandpass filtering is used to separately filter out the respiration and pulse rate information [6].

After filtering, the frequency domain evaluation methods, such as the Fast Fourier Transform (FFT) method, are commonly used to measure respiratory and cardiac rates. In the presence of large amounts of noise and a weak cardiac signal, the methods of noise reduction, time-series smoothing, or high-resolution spectral estimation can be applied in order to improve the accuracy of the results of vital-sign monitoring [1].

To sum up, the conceptual basis of physiological parameter monitoring based on millimeter-wave radar is the series of signal transformations of the type respiratory micro-movements-echo phase modulation-frequency attribute analysis. With this approach, the study of multi-person monitoring of vital signs can be conducted; however, in case of a group of objects under investigation, the phase will overlap, so the ability to distinguish between the signals of various individuals will be paramount.

3. Literature Review

3.1 Signal Separation in Multi-Person Monitoring

When using millimeter-wave radar to monitor vital signs, the main function is to detect the respiration rates and heartbeats based on the change in the phase of echoes caused by small chest movements. In the case of an isolated object, the standard procedure is to estimate the distance to the object and then filter or perform spectral analysis of the phase measurements at the object, which allows obtaining the necessary physiological parameters. This is why the greatest challenges in identifying individuals are: how to boost weak signals, how to reduce the influence of noise, and how to achieve accuracy in frequency estimation [1].

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Nonetheless, the problem becomes more complex with the increase in the number of people being monitored, starting with one person and going up to many. Even at the same distance of radar detection, each person will reflect the radar waves differently, and even small movements caused by breathing and heartbeat will influence the echo. This radar return that is observed at this particular moment does not correspond to a single target, but denotes the combined returns of different targets. In elementary terms, the radar measurements from several sources may be described as follow:

$$s(t) = s_1(t) + s_2(t) + \cdots + s_n(t) + \omega(t) \quad (2)$$

Here, $s_i(t)$ represents the vital sign echo component associated with the i-th target, and $\omega(t)$ represents the noise and interference term. From this perspective, monitoring multiple vital signs should not focus solely on how to acquire the vital signals; it should also consider how to appropriately separate the signals emitted by each individual.

With respect to this underlying issue, existing research has generally followed a developmental path that includes physical-level separation and algorithm-level isolation, and finally data-oriented modeling. Historically, the range resolutions of the FMCW systems were used to detect targets; at close range, the angular resolution of MIMO radar provided additional information; if hardware could not provide the required resolution, methods of decomposing signals were used; most recently, there has been an attempt to use deep learning as a form of data-based automatic generalization of complex radar phenomena. The next sections will classify related literature according to this exact order.

3.2 Distance-Based Separation Methods

The isolation methods of distance are among the first technical methods applied in multi-person physiological-signs monitoring. It can be summarized as using the distance-selective properties of FMCW radar to recognize human objects, that is, to find the location of distinct persons by distance. In FMCW radar systems, a waveform is combined to produce an intermediate-frequency output, which is then processed using a range-direction Fast Fourier Transform (Range FFT) to yield a distance profile. Assuming that the distances between the detected subjects and the sensor differ and such gaps exceed the radar resolution limit, individual peaks corresponding to each person will be observed in this distance profile.

Afterward, the investigators have the opportunity to pick and choose the phase information associated with particular distance parts and apply it to the selected signals with phase stretching, bandpass filtering, and spectral estimation to obtain respiratory and cardiac data of each subject. The method follows an explicit conceptual framework: first, target detection is done based on range data, and second, physiological monitoring is done in every distance unit having a detected person. Subsequently, due to the presence of humans in confined spaces and significant differences in distance, distance-based separation methods offer advantages such as simple implementation and a low processing load.

However, such a strategy has various limitations. To start with, it makes an assumption based on the fact that there is a significant distance difference between the objects. In case the subjects are very close to each other, or belong to the same volumetric bin, the echo responses of different people will overlap in terms of the distance axis, and therefore the individual vital signs cannot be obtained by focusing on any specific distance peak. Also, at home, multipath scattering caused by surfaces and other objects might contaminate the range spectrum (e.g., by creating phantom peaks or broadening the target profile), which will also affect proper target detection and correct data processing or derivation [7].

In turn, despite the fact that the distance-oriented partitioning technique is the main structure of multi-person physiological tracking, its applicability to practical use is still limited to some extent. If the study subjects change to a group, the initial loose scatter and wide-spread to another group, which is closely located or of different postures, using only spatial distance measures may not provide strong identification. To overcome this problem, researchers have begun to use spatial angular information to better identify the targets.

3.3 Spatial Separation Methods Based on MIMO Radar

Spatial partitioning technologies in MIMO radar are a more advanced form of distance-based separation methods. This kind of radar is necessary because there are instances when many people are present at the same time, with the targets involved possibly being nearby in range but not necessarily residing on the same azimuth

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(as perceived by the radar). Through the use of angular data, there is another dimension of separation that can be added to the range dimension, allowing further ability to distinguish between multiple objects.

The MIMO radar uses a large number of transmitting and receiving antennas to create a synthetic aperture, enabling the radar system to obtain information on the position and orientation of a target. The underlying principle is that as reflected echoes at non-identical angles strike the antenna array, they induce phase changes in the different reception pathways. These phase changes between channels are analyzed to determine the direction of arrival (DOA) of the target. In practical applications, angle detection has been implemented using beamforming and the MUSIC method. The architecture is able to discriminate human targets with different angles in the angular space by implementing this strategy to process the information [8].

Spatial partitioning methods are contrary to distance-dependent isolation methods and have the benefit of using both spatial distance and angular information simultaneously. MIMO systems can successfully detect a number of targets that are almost close but positioned in different azimuthal locations. Therefore, this approach is better suited to the surveillance environment, such as hospital rooms, homes, and indoor space, where people are configured in complex layouts.

However, the spatial division method has not yet been able to solve all the problems in the multi-person bio-signal monitoring system. Technologically speaking, such systems often rely on multi-channel sensors and precise synchronization equipment, resulting in complex structures that cost more than single-channel radars. Angular accuracy also depends on the size of the antenna or number of array elements. In case the directions of the subjects are too close, the device could not recognize them correctly [9]. Besides, real people are not point mass objects, and their poses and minor movements may cause angle predictions to be unreliable.

Therefore, despite the fact that MIMO radar enhances the ability to detect multiple individuals in the physical space, it is still limited physically and in terms of positional resolution. With the difficulty of separating objects based on their range and orientation, researchers have begun exploring methods of decomposing signals that analyze the combined data to extract the physiological signature components of individual persons.

4. Key Findings

4.1 Multi-person Vital Signs Monitoring Technology is Shifting from Physical Separation to Intelligent Separation

A review of modern literature suggests that there has been a characteristic chronological development of multi-person millimeter-wave radar-based monitoring systems of vital signs [10]. Early tests were mostly based on the natural distance resolution capabilities of FMCW radar, using Range FFT to distinguish several people in space. The method has a simple structure and low processing workload, but requires significant object separation. As multi-person tracking settings became more complex, researchers also combined MIMO radar to enhance target discrimination by adding angular information [11] so that the device can still maintain some level of recognition even when the objects are almost touching. Recently, the focus of research has shifted away from assessing physical spatial separation toward analyzing signal attributes and data-driven modeling, with a research model in which signal decomposition and deep learning approaches are advancing in tandem. It shows that multi-person vital signs monitoring technology is moving away from reliance on hardware accuracy towards reliance on the intelligent interpretive capability of algorithms.

4.2 Different Technical Approaches are Complementary; There is No Single Optimal Solution

Recent research implies that different technical frameworks have individual values and suitable application conditions. Isolation methods based on distance are easy to implement and have great time efficiency, making them perfect in situations where objects are scattered far and wide; spatial isolation plans based on MIMO radar can make effective use of angular information to increase the ability to recognize many objects, but they require a lot of equipment costs and technical details; signal decomposition-based approaches have some level of overcoming the limits of physical resolution, but they are quite dependent on statistical properties of signals and configuration parameters; deep learning-based paradigms are capable of extracting feature patterns when

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used in complex environments and show significant practical potential in non-linear, multi-target environments; however, their effectiveness remains limited by such factors as the size of the data set, architectural flexibility, and the amount of processing. As a result, there is no universal or monolithic strategy that may be implemented in all deployment scenarios at present, and the synergetic and hybrid development of various technical forms has become a major trend in modern research.

4.3 The Focus of Research is Gradually Shifting from Algorithm Verification to Applications in Complex Scenarios

As the millimeter-wave radar hardware capabilities persistently improve and the methods of signal processing constantly improve, the studies of vital-signs detection have shifted over time towards real-life applications in complex conditions. In recent years, many scholarly articles have focused on practical applications such as patient monitoring in clinical departments, intelligent elderly care, home health monitoring, sleep measurement, and rescue services [12]. In these scenarios, factors such as population development, changes in body positions, occlusion, multipath dispersion, and background noise can all play a role in determining the effectiveness of identifying vital signs. Therefore, improving the performance of a particular algorithm is no longer enough to meet practical needs. What should be done to use radar hardware architecture, target recognition, signal processing, and smart algorithms to achieve reliable, accurate, and instant physiological indicator tracking with complicated conditions has become one of the main avenues of advancement of millimeter wave radar vital-signs monitoring.

5. Discussion

5.1 The Integration of Multiple Technological Approaches Will Become a Key Direction for Development

However, an overview of recent literature suggests that despite each methodology having particular advantages, they all at the same time have significant limitations. Isolation methods based on distance can be computationally efficient, but they are limited by their spatial resolution; MIMO spatial separation may provide additional angular information, but it requires advanced hardware architecture; signal disentanglement methods may improve the capacity of combined signals, but they are highly sensitive to preliminary hypotheses; and deep learning models have strong nonlinear representation capabilities but suffer from problems such as large data requirements and lack of model transparency. Future studies should therefore focus not on one approach that will completely replace other ones, but on the proper use of the combined benefits of different technical paradigms. As an example, distance data might be applied to the initial target location, and then spatial data might be used to improve the capability of target differentiation and also combined with signal disentanglement and deep learning plans to obtain accurate physiological sign extraction and thus develop a sounder and more effective multi-person vital sign monitoring system [13].

5.2 Engineering Applications Still Need to Address Issues Related to Data, Computing Power, and Standardization

To date, most of the research on the monitoring of vital signs with millimeter-wave radar focuses on laboratory testing, and there is a difference between this type of work and application in practice. To start with, the number of readily available datasets of vital signs is limited, and there is a huge disparity in the specification of radars, test conditions, and measures of assessment used across studies that hinder the process of consistent evaluation of different algorithms and limit the transferability of deep learning models [14]. Second, despite the ability of deep learning structures to be more effective in detecting objects in complex situations, they require high levels of computation, which remain a challenge in real-time implementation on peripheral devices and energy-saving radar devices. Additionally, an open gap in the standardization of data collection procedures and rating systems of multi-person vital sign detection currently exists, which prevents the development of related technologies in a systematic fashion.

As we progress, since millimeter-wave radar hardware performance is still being improved, the size of accessible data repositories increases, and AI methods keep developing, multi-person vital sign tracking is expected to become more stable, precise, and self-monitoring capable. On the basis of such a foundation,

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technology will play a much more decisive role in the fields of intelligent medical care, home-based assistance to older people, the recording of sleep, safety in society, and rescue operations. Such technology could also provide more reliable technical support for non-contact vital sign monitoring implementation into practice.

6. Conclusion

The given manuscript provides an organized analysis of non-contact vital-parameter tracking systems based on millimeter-wave radar with an emphasis on the current technological environment and critical technical characteristics in the context of monitoring several people. At first, it defines the main principles of detecting the physiological indicators through FMCW millimeter-wave radar, clarifies the relationship between chest cavity micro-movements and echo phase variations, and describes the signal extraction process. The use of this framework allowed us to review famous studies in the field of multi-person monitoring and, tracing the development of technical improvement, to synthesize and compare the major methodological approaches, including distance-based, spatial-based, signal-decompositional and deep-learning-oriented ones.

As an extensive review of the available literature shows, the multi-person vital-signs detection methods have over time evolved in such a way as to reduce focus on spatial isolation towards more complex and analytical frameworks based on data. Regardless of the different technical methods having various advantages, all have particular limitations; at the moment, there is no single method that can be applied to any of the complex situations. In the future, new developments in multi-source data integration, signal filtering, and efficient millimeter-wave radar hardware will still drive the development of multi-person vital signs tracking systems into greater precision, better stability, and wider practical applications.

To sum up, millimeter-wave radar that is non-invasive, highly accurate, and private shows great potential in application in such areas as smart medical care, home-based elderly care, sleep monitoring, and crisis response. In line with the development of hardware to be used in radar, signal processing methods are developing, and artificial intelligence is developing; non-contact vital-sign detection of several people should be expected to become more stable, efficient, and intelligent, providing important technical support to the future evolution of intelligent health monitoring systems.

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Conflicts of Interest

The authors declare no conflict of interest.

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