Autonomous Integrated Sensing and Processing for BioRadar: Advancing Non-Invasive Biomedical Monitoring and Signal Analysis

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***Abstract*— This paper presents a novel automated system that leverages a Raspberry Pi to operate a 24 GHz single-channel continuous wave (CW) radar for through-the-wall concurrent vital sign monitoring of two subjects. The system autonomously performs independent component analysis using the joint approximation diagonalization of eigenmatrices (ICA-JADE) to separate both individuals' breathing rates (BR). It applies the maximal overlap discrete wavelet transform (MODWT) after ICA-JADE to extract heart rates (HR). By integrating the radar system and ICA-JADE into an embedded platform, the system operates without requiring manual intervention. The automation framework enables real-time processing, enhancing the system's practical deployment in real-world applications. The results demonstrate high accuracy in isolating BR and HR using ICA-JADE, as benchmarked against conventional chest belts and ECG measurements. This fully automated approach shows significant potential for applications such as search and rescue operations, security surveillance, and remote healthcare monitoring through barriers.**

***Keywords*— Doppler radar, CW, raspberry pi, through-the-wall, Bioradar**

I. Introduction

Non-contact, through-the-wall vital sign monitoring is a valuable technique for applications like search and rescue, surveillance, and military operations [1]. It detects vital parameters such as heartbeat and respiration without physical contact, which is crucial in scenarios with limited or dangerous access. Advances in radar and ultra-wideband technologies have improved accuracy, making these systems more effective. Unlike traditional methods using cameras [2], [3], LiDAR [4], and acoustic sensors [5], radar can penetrate walls and debris to detect vital signs reliably [1]. However, interference from closely spaced objects in the radar's field of view complicates signal processing [6]. Multi-subject scenarios further challenge vital sign extraction due to obstruction issues [7].

Recent studies have explored UWB, stepped-frequency CW (SFCW), and CW radars for through-the-wall detection of multiple subjects' vital signs. UWB radar demonstrated potential in detecting two subjects' respiration through a 9-cm wood wall [8], but wall materials and noise limited performance. Enhanced deep learning models with attention mechanisms detected up to four subjects [9], and SFCW radar used k-means clustering to locate three closely spaced individuals [10]. However, none extracted both breathing and heart rates, which is critical for post-disaster scenarios. We propose an autonomous system integrating a 24 GHz CW radar and a Raspberry Pi 4B to continuously extract vital signs, even with one person obstructing another. Local processing on the Raspberry Pi provides real-time monitoring, enhancing energy efficiency, data security, and reducing transmission needs. The core contributions include:

1. Using CW radar with ICA-JADE to extract breathing and heart rates in occluded scenarios.
2. Real-time data processing on a Raspberry Pi for continuous monitoring.

II. Theoretical Background

A. Through-the-Wall Vital Sign Monitoring of Multiple Subjects

A CW radar continuously transmits a signal through a wall to sense minute chest displacements of a human subject. The phase shift in the reflected signal, caused by the tiny movement of the chest surface, is directly proportional to the displacement and can be expressed as:

$$\theta(t) \propto \frac{4\pi}{\lambda} x(t) \tag{1}$$

where $x(t)$ denotes the periodic small chest displacement that carries breathing and heart rate information. The radar-received signal is attenuated due to absorption and the properties of the wall, such as its thickness and material composition, and can be expressed as:

$$R(t) = A_R \cos\left[2\pi f_c(t - t_d) + \phi(t - t_d) + \Theta_0\right] \tag{2}$$

where t_d is the round-trip delay and A_R is the amplitude of the reflected signal, given by $A_R = a \times w \times c$, with a, w, and c representing the complex transmission coefficients for the air, wall, and chest, respectively. When multiple subjects are within the radar's field of view (FOV), the multiple reflected RF echoes from the chest walls cause interference, leading to a complex mixture of the received signal, expressed as:

$$M_n(t) = \cos(2\pi f_c t) \cdot \left[R_1(t) + R_2(t) + \cdots + R_n(t)\right] \tag{3}$$

B. ICA-JADE

When two subjects are within the same beamwidth, the ICA-JADE algorithm can be utilized to separate their individual breathing and heartbeat signals from the complex mixture. The two mixed signals, y_1 and y_2, are linear combinations of the two source signals, s_1 and s_2, and are expressed as follows:

$$\mathbf{Y} = \mathbf{KS}, \quad \text{where} \quad \mathbf{K} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix}, \quad \mathbf{S} = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \tag{4}$$

Here, K stands for the mixing matrix, while S represents the matrix containing the source signals. The objective of ICA is to determine the separating or demixing matrix, $W = K^{-1}$. As a result, the recovered source signal can be expressed as:

$$S = WY. \tag{5}$$

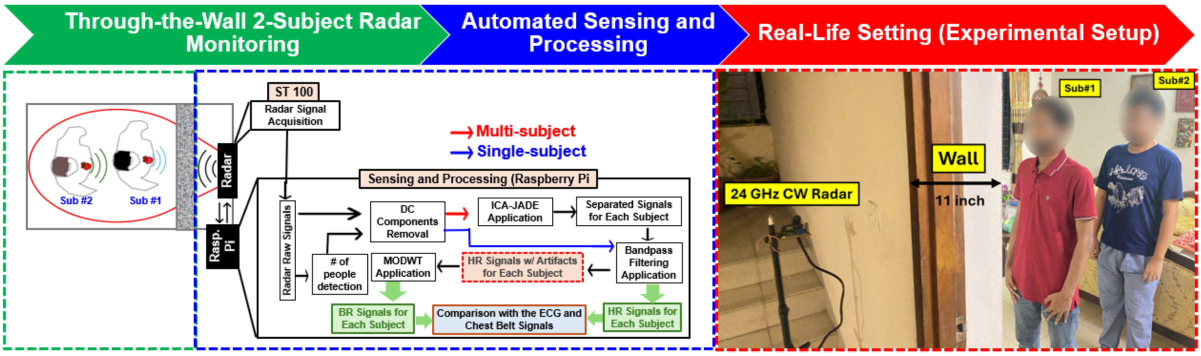

Fig. 1. Pictorial representation of the conceptual and experimental setups for the automated radar-based vital signs monitoring system, showing *(from left to right)* two subjects standing in a file formation (one behind the other) being monitored by radar, radar signal processing, and display handled by a Raspberry Pi, as well as the real-life setting.

ICA-JADE has demonstrated promising results with an accuracy of at least 90% when compared to EMD (empirical mode decomposition) to separate the simultaneous heartbeat waveforms of two subjects within the beamwidth [11]. This work aims to apply this method to separate the two subjects' heartbeat waveforms simultaneously. The extracted source signals require denoising to address intermodulation tones caused by the radar module's nonlinear mixer and to reduce interference from unintended body motion, which creates dominant subharmonics in the frequency spectrum alongside the primary chest movement signal [12].

C. MODWT

This work combines Maximal Overlap Discrete Wavelet Transform (MODWT) with ICA-JADE to denoise the signal, and subharmonics obstruct desired heart rate signals. In this work, extracted source signal $s(t)$ is decomposed into two components using the MODWT method [13]. The approximation component and detailed component are expressed as:

$$s(t) = \sum_{n} c_{j,n}\phi_{j,n}(t) + \sum_{j=J}^{\infty}\sum_{n} d_{j,n}\psi_{j,n}(t) \qquad (6)$$

where $\phi(t)$ is the scaling function corresponding to the approximation coefficient $\{c_{j,n}\}$, while $\psi(t)$ represents the wavelet function associated with the wavelet coefficient $\{d_{j,n}\}$. The MODWT multiresolution analysis approach decomposes the original signal into approximation and detailed components without down-sampling, allowing efficient extraction of fundamental frequencies, subharmonics, and intermodulation-related components [13]. Recently, the efficacy of the MODWT method was demonstrated by effectively suppressing the subharmonics of the heartbeat signal, thus significantly improving the heart rate signal and accuracy [14].

III. Materials and Methods

A. Experimental Setup & Data Acquisition

A 24-GHz single-channel CW radar (K-LC1a module, RFbeam Microwave, Switzerland) with an 80°/34° beam aperture was used in this experiment. The radar is connected to an ST100 starter kit for data acquisition. Two male subjects (ages 21–25, no history of heart or breathing issues) stood before each other, with Sub#1 positioned 1.5m from the radar behind an 11-inch brick wall and Sub#2 0.5m behind Sub#1. The radar was mounted 1m above the ground to align with chest level. Five 1-minute data sets were collected for each scenario. Reference breathing rates were measured using a Go Direct® Respiration Belt and analyzed with Vernier software, while ECG data was collected with a BSL MP46 from BIOPAC Systems. The Faculty of Biological Sciences, University of Dhaka's ethical review board approved the experiment.

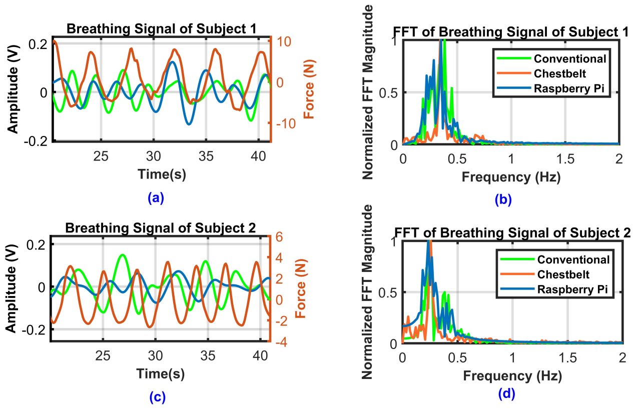

Fig. 2. Separated breathing waveforms of (a) the 1st and (c) the 2nd subjects, acquired using the Raspberry Pi, compared to the reference chest belt and conventional results, along with their respective FFTs: (b) FFT for the 1st subject and (d) FFT for the 2nd subject, obtained using ICA-JADE.

B. System Workflow and Audio Processing Algorithm

Algorithm 1 System Workflow and Radar Signal Processing

```
function PROCESSRADARSIGNAL(pre_sig)
    HR_sig, BR_sig ← bandpass_filter (pre_sig)
    HR_freq, BR_freq ← perform_fft (HR_sig, BR_sig)
    return HR_sig, BR_sig, HR_freq, BR_freq
end function
while True do
    count ← detect_number_of_people()
    if count == 0 then
        wait for person to be detected
    else
        raw_sig ← record_signal_from_ST100()
        pre_sig ← DC_comp_removal(raw_sig)
        if count == 1 then
            Sb1_BR, Sb1_HR ← processRadarSignal(pre_sig)
        else if count == 2 then
            Sb1_sig, Sb2_sig ← separation_using_ICA_JADE(pre_sig)
            Sb1_BR, Sb1_HR ← processRadarSignal(Sb1_sig)
            Sb2_BR, Sb2_HR ← processRadarSignal(Sb2_sig)
            perform_MODWT(Sb1_HR)
            perform_MODWT(Sb2_HR)
        end if
        plot_results()
    end if
end while
```

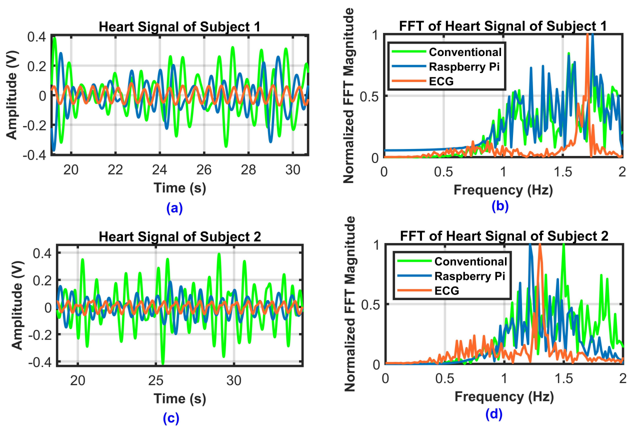

Fig. 3. Separated heart signals of the (a) 1st and (c) 2nd subjects, acquired using the Raspberry Pi, compared to the reference chest belt and conventional results, along with their respective FFTs; FFT for the (b) 1st and (d) 2nd subjects, obtained using ICA-JADE and MODWT.

The system is implemented on a Raspberry Pi 4B (4GB), integrating the ST100 acquisition module for real-time physiological signal analysis. The ST100 records audio signals through high-sensitivity antennas designed to detect subtle chest movements, enabling the extraction of heart rate (HR) and breathing rate (BR). The Raspberry Pi processes signals locally, first removing DC components. Then, by applying the ICA-JADE algorithm, the mixed signal is separated into two independent vital sign signals. A 3rd-order Butterworth filter isolates HR and BR, with cut-off frequencies of 0.2–0.4 Hz for BR and 0.8–2 Hz for HR. The Modified Discrete Wavelet Transform (MODWT) refines the heart signal by isolating the fundamental frequency, reducing artifacts. Finally, FFT analysis identifies the highest magnitude frequency as the BR and HR. We compared our results to reference measurements from a chest belt and ECG to validate them. It is important to note that no personal data is stored or shared, ensuring user privacy.

IV. Results

We plotted the reference and radar results from the conventional method and Raspberry Pi on the same graph to better visualize our results. All the signals and their FFTs were plotted to understand the accuracy of the overall system better (see Figs 2 & 3). Fig. 2 shows the two subjects' separated breathing signals from the conventional method, Raspberry Pi, and reference chest belt, along with their respective FFTs. It can be seen that the number of breathing cycles from all the radar results matches that of the reference chest belt [Fig. 2(a & c)], which is demonstrated on the FFT plots [Fig. 2(b & d)]. The highest magnitude of the FFT plot of the radar results, corresponding to the breathing rate, matched that of the reference chest belt, indicating excellent accuracy. The separated heart signals of the two subjects after applying MODWT using the conventional method and Raspberry Pi and the reference ECG signals have been shown in Fig.3 along with their respective FFTs. The ECG signals have been filtered from 0.8 Hz to 2 Hz using a 3rd-order Butterworth band-pass filter to better compare with the radar heart signals. The highest FFT magnitude of the radar heart signal matched very closely with the reference ECG, as seen from Fig.3(b, & d). As HR fluctuates quite often, we can see some differences in the FFT peak comparison. For Sub#2, the HR fluctuated more than Sub#1. It was due to Sub#2 being behind Sub#1, causing more interference in the reflected signal. Overall, satisfactory results were obtained for the two subjects' BR and HR signals.

V. Conclusion

In this article, an autonomous through-the-wall concurrent vital sign monitoring system using a Raspberry Pi and single-channel CW radar has been reported to monitor breathing and heart rates continuously. Using the Raspberry Pi to capture the radar data and implement the ICA-JADE algorithm, we successfully separated the BR of subjects standing in a line formation, and the results show excellent agreement with those obtained from the Vernier respiration belt used as a reference. Similarly, the HR of each subject using ICA-JADE and MODWT in the same setup was obtained. The results strongly agree with those from the Biopac chest belt BSL MP46 used as a reference. The compact and simple architecture of the Raspberry Pi and CW radar provides a great advantage for applications in life signs detection under the rubble, post-disaster search and rescue, and other scenarios where contactless-continuous monitoring is required.

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