Enhanced Motion Sensing with Millimeter-wave Radar and Its Biomedical Application

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***Abstract*—Millimeter-wave radar is widely used for motion sensing, but when motion amplitude is smaller than deep sub-wavelength, traditional methods fail due to a short *I/Q* trajectory. This project proposes a reconfigurable virtual continuous-wave algorithm (RVCWA) to enhance radar sensitivity to micrometer-scale motion. The frequency-modulated continuous-wave (FMCW) radar is modeled as multiple CW radars with different frequencies, and the multiplication of single-tone signals is reconfigured to a higher-frequency CW signal, improving micromotion detection. Experiments demonstrate that the algorithm can recover sinusoidal motion with a 10 μm amplitude (1/500 λ at 60 GHz), achieving a root mean square error of 3.55%, a 2.3-fold improvement over traditional methods. Additionally, a cardiac motion monitoring experiment validates its potential for biomedical applications.**

***Index Terms*—circle-fitting, cardiac motion monitoring, deep sub-wavelength displacement, FMCW radar, motion sensing.**

I. INTRODUCTION

In recently years, millimeter-wave radar has gained significant attention due to its sensitivity and precision, enabling applications in vital sign monitoring [1], human-machine interaction [2], and indoor motion sensing [3]. Despite these advancements, millimeter-wave radar technology continues to face significant challenges in detecting exceedingly subtle motions.

For radar-based sensing, pre-calibration is crucial for phase demodulation to address amplitude mismatch and DC offset in *I/Q* signals caused by circuit inconsistencies. The commonly used pre-calibration method is circle-fitting [4]. However, when detecting small displacements, the *I/Q* signal's arc length on the unit circle is often too short, which makes it difficult for the circle-fitting method to accurately localize the circle's center [5]. This issue results in distortions in both amplitude and shape in the recovered displacement.

This project introduces a novel reconfigurable virtual continuous-wave algorithm (RVCWA) that increases the *I/Q* trajectory length by combining multiple single-tone signals to form a higher-frequency CW signal. This extension enhances the accuracy of the circle-fitting method, enabling more precise detection of small motions.

II. THEORY

The FMCW radar transmits chirp signals and receives the reflections from the target. The transmitted and received signals are mixed to generate the beat signal, which can be modelled in discrete form as

$$s_b[m,n] = \exp\left(j\left(\frac{4\pi BR[m]}{Nc}n + \frac{4\pi f_c R[m]}{c} + \Delta\varphi\right)\right)$$
$$= \exp\left(j\frac{4\pi R[m]}{c}\left(f_c + B\frac{n}{N}\right) + \Delta\varphi\right) \qquad (1.1)$$

where f_c is the center frequency, B is the bandwidth, N is the number of sampling points, c is the light speed, $R[m]$ is the target's motion, defined as the nominal distance d_0 plus displacement $x[m]$, $R[m]=d_0+x[m]$, n is the "fast time", while m is the "slow time", The residual video phase $\Delta\varphi$ is negligible [6]. The data matrix of the beat signal is shown in Fig. 1(a), consistent with (1). From (1), it is evident that the n*th* column of the data matrix s_b can be considered as a single-tone signal with a frequency of $f_c + Bn/N$. Therefore, an FMCW radar can be treated as N independent CW radars. For any two of these single-tone signals, their dot product yields

$$s_{RVCW} = s_b[m,n_1].*s_b[m,n_2]$$
$$= exp\left(j\frac{4\pi R[m]}{c}\left(2f_c + B\frac{n_1+n_2}{N}\right)\right) \qquad (2)$$

A higher-frequency CW signal is virtually reconfigured, resulting in an arc length roughly twice that of the single-tone signal, as shown in Fig. 1(b) and 1(c). This improves the accuracy of circle-fitting and enhances the precision of

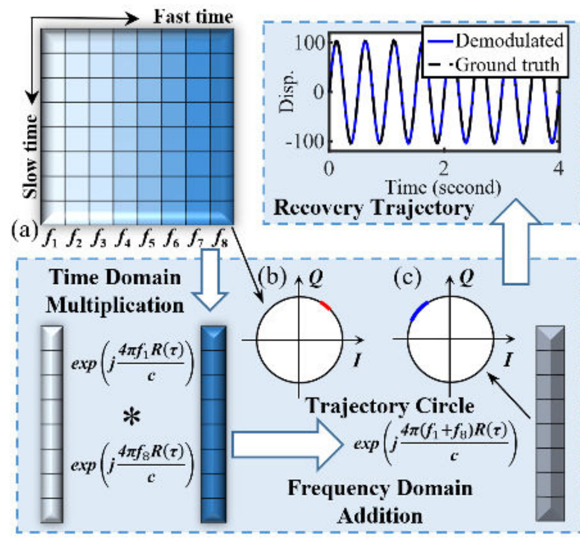

Fig. 1. Flowchart of the proposed RVCWA for enhanced motion sensing: (a) the data matrix of beat signal, (b) the arc trajectory of the single-tone signal, (c) the arc trajectory of the reconfigured CW signal.

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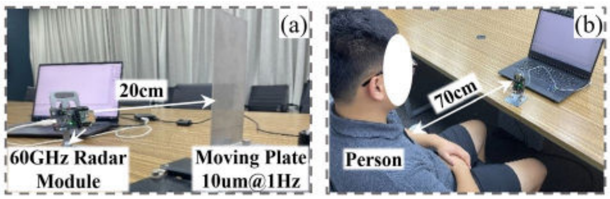

Fig. 2. Experimental setup: (a) standard actuator motion, (b) cardiac motion monitoring.

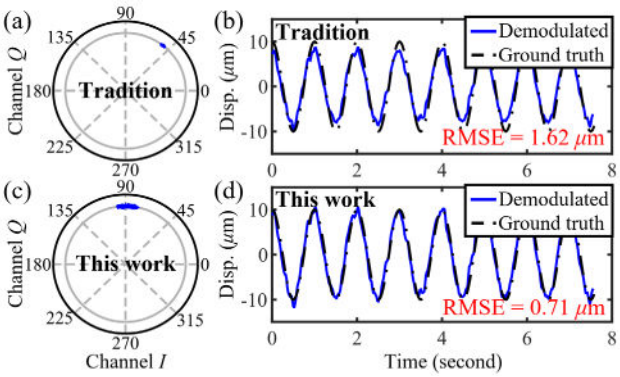

Fig. 3. Standard actuator motion: (a) circle-fitting result of traditional algorithm, (b) demodulated displacement from (a), (c) circle-fitting result of proposed RVCWA, (d) demodulated displacement from (c).

detecting subtle motion. All pairs of single-tone signal sets that can be virtually reconfigured to the same frequency f_3 ($f_3=2f_c+Bn_3/N$) are summed to improve the signal-to-noise ratio (*SNR*).

$$s_{RVCW2} = \sum_{n_1} s_b[m,n_1].*s_b[m,n_3-n_1] \quad (3)$$

While only the multiplication of two single-tone signals is discussed, the algorithm can also be applied to multiple single-tone signals to reconfigure a higher-frequency CW signal.

III. Experiments

To validate the RVCWA, a standard linear stage motion experiment was conducted. The chirp signal was configured with a start frequency of 57 GHz, a bandwidth of 4 GHz, and an 80 μs ramp-up time. The experimental setup is illustrated in Fig. 2(a), where the moving plate is placed at a nominal distance of 20 cm from the radar. The linear stage undergoes sinusoidal motion with a 10 µm amplitude (1/500 λ @ 60 GHz) and a 1 Hz frequency. The small motion amplitude makes it difficult for the traditional algorithm to locate the arc's center, leading to distortions in amplitude and shape in the recovered displacement, as illustrated in Fig. 3(a) and 3(b). The RMSE of the recovered displacement using the traditional algorithm is 8.1%. In this scenario, the RVCWA employs a virtual CW signal with a frequency of 236 GHz (59 GHz * 4). The arc trajectory of the I/Q signals and the reconstructed displacement of the moving plate are depicted in Fig. 3(c) and 3(d), respectively. The RVCWA increases the arc length by around 4 times, as shown in the arc trajectory analysis, which allows for more accurate circle-fitting. The recovered displacement has an RMSE of 3.55%, improving 2.3 times over the traditional algorithm.

Vital sign detection, a prominent application of millimeter-wave radar, is employed to assess RVCWA performance. The

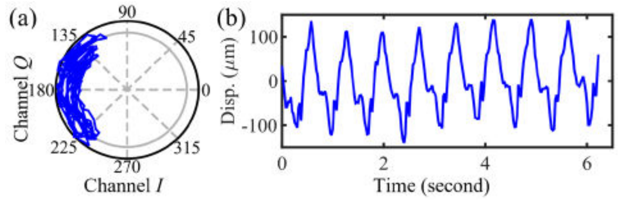

Fig. 4. Cardiac motion monitoring: (a) circle-fitting result of cardiac motion *I/Q* signal obtained by the RVCWA, (b) demodulated displacement from (a).

cardiac motion detection setup is shown in Fig. 2(b), where the subject seated 70 cm from the radar and maintaining breath-holding. Fig. 4(a) illustrates the arc trajectory corresponding to the cardiac motion obtained by the proposed algorithm, with the arc length magnified to over a quarter of the circumference. Fig. 4(b) depicts the reconstructed cardiac motion by the proposed RVCWA. This graphical depiction clearly highlights the algorithm's ability to accurately restore the complex waveform.

IV. Conclusion

In this project, the RVCWA is proposed for the enhanced motion detection using FMCW radar. The algorithm transforms an FMCW radar into multiple CW radars and combines single-tone signals to generate a higher-frequency CW signal. This increases the arc length of the I/Q trajectory, improving circle-fitting calibration. This, in turn, elevates the capability to sense extremely subtle motions. The experimental results further underscore that the RVCWA, in comparison to the traditional algorithm, achieves finer recovery of micrometer-scale motion. The experimental results also demonstrate that the proposed algorithm can monitor cardiac motion with great precision.

V. Impact Statement and Future Plans

The MTT-S scholarship has not only supported me in completing this project but also served as an honor that motivates and inspires me to continue pursuing my passion for scientific research. As a result, I have applied for successive postgraduate and doctoral programs of study program and am currently working towards my Ph.D. degree.

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