Through-the-Wall Human Motion Detection and Localization with Two Continuous Wave Radars

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***Abstract*—This paper presents a low-cost RF sensing system for human activity detection and localization using two continuous wave (CW) radars. By strategically positioning the radars, motion is effectively detected with minimal ambiguity. A simple localization method is proposed and shown to achieve Cramér-Rao Bound (CRB) under equal range estimation variance. Experimental results using off-the-shelf software- defined radios (SDRs) validate the system's effectiveness in through-wall scenarios.**

I. INTRODUCTION

Through-wall human activity detection is critical for security and rescue applications. Traditional sensing methods struggle in non-line-of-sight conditions, while RF-based techniques provide robustness and cost efficiency [1], [2]. CW radar is particularly effective for detecting motion via Doppler shifts. Dual-frequency CW radar (DFCWR) further estimates range from phase differences [3], [4].

Existing monostatic CW radars suffer from low Doppler returns when motion is non-radial and are affected by multipath [5], [6]. To overcome these challenges, we deploy two radars behind orthogonal walls. This configuration reduces localization ambiguity while maintaining system simplicity. Our approach achieves near-CRB performance under equal range estimation variances.

II. SYSTEM OVERVIEW AND SIGNAL PROCESSING

As illustrated in Fig. 1, our setup consists of two radars positioned behind orthogonal walls. The system operates in either a fully monostatic mode or a hybrid mode with one monostatic and one bistatic station.

The received signal undergoes zero Doppler cancelation using an extensive cancelation algorithm [7]. The resulting signal is processed using a short-time Fourier transform (STFT) to extract Doppler features. Dual-frequency ranging estimates the target's range from the phase difference at two carrier frequencies:

$$r^p(t) = \frac{c}{4\pi(f_1 - f_2)}(\phi_1^p(t) - \phi_2^p(t)). \tag{1}$$

where c represents the speed of light, f_1 and f_2 denote the first and second carrier frequencies, respectively, and $\phi_1^p(t)$ and $\phi_2^p(t)$ represent the measured phases of the received signal at time t, respectively.

III. LOCALIZATION METHOD

For two radar stations at $\boldsymbol{s}_1 = (0,0)^T$ and $\boldsymbol{s}_2 = (b,0)^T$, range estimates r_1 and r_2 provide target position (x, y):

$$x = \frac{r_1^2 - r_2^2 + b^2}{2b}, \quad y = \pm\sqrt{r_1^2 - x^2}. \tag{2}$$

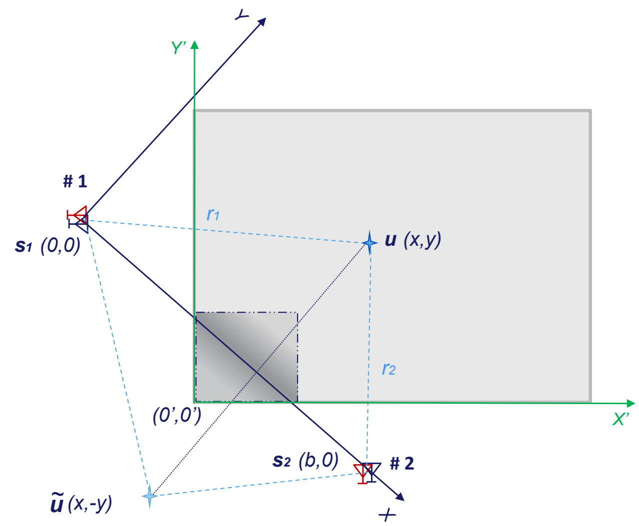

Fig. 1. Localization using two radar stations

Ambiguities arise when the target moves into specific regions where both solutions are feasible. To mitigate this ambiguity, radar units can be placed farther away from the walls, increasing the stand-off distance. To determine whether a location falls within the room, a transformed coordinate system (X', Y') with the room's lower-left corner as the origin, is employed (as shown in Fig. 1). The transformation between the two coordinate systems, (X, Y) and (X', Y'), involves a combination of translation and rotation. It is important to note that y can become imaginary due to measurement errors in r_1 and r_2. When this occurs, the corresponding range estimation is discarded to maintain accuracy.

When multiple range estimates are available, they can be fused for improved accuracy. Given that the measurement noise of two radar units follows a Gaussian distribution with zero mean and variances σ_1^2 and σ_2^2 , respectively, the CRB of the target location is:

$$\mathrm{CRB}(\boldsymbol{u}) = \frac{1}{N}\left[\nabla_{\boldsymbol{u}}^T(\bar{\boldsymbol{r}}(\boldsymbol{u}))\begin{bmatrix}\frac{1}{\sigma_1^2} & 0\\ 0 & \frac{1}{\sigma_2^2}\end{bmatrix}\nabla_{\boldsymbol{u}}(\bar{\boldsymbol{r}}(\boldsymbol{u}))\right]^{-1} \tag{3}$$

where N denotes the total number of range estimates, and $\nabla_{\boldsymbol{u}}(\bar{\boldsymbol{r}}(\boldsymbol{u}))$ is the gradient of $\bar{\boldsymbol{r}}(\boldsymbol{u})$ with respect to $\boldsymbol{u}$.

IV. EXPERIMENT RESULTS

This section evaluates the performance of our two-station RF human activity sensing system in a 3m × 3m room

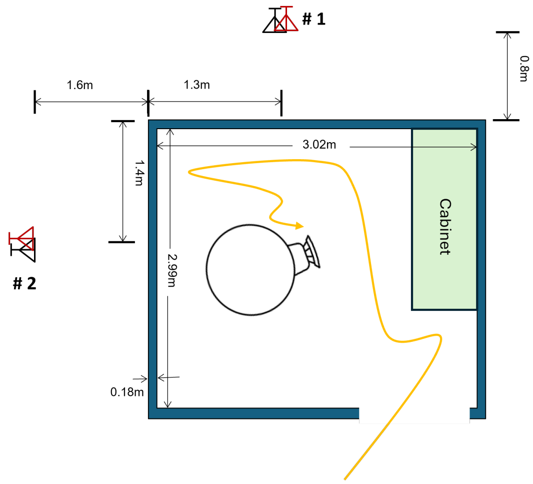

Fig. 2. Room layout and moving trajectory of the individual

Fig. 3. Photo of our SDR-based CW radar station #2

with a through-the-wall setup. The room layout, including the positions of the two radar stations, is depicted in Fig. 2. Each radar station uses SDRs — the USRP-2954 and USRP-2955 (both from National Instruments) — as the transmitter and receiver, respectively, as shown in Fig. 3.

A dual-frequency signal centered around 3.5 GHz is transmitted to capture the Doppler frequency of the moving human target while ensuring adequate wall penetration. The dual-frequency signal can either be a minimal-bandwidth dual-tone signal or a signal with limited bandwidth, significantly lower than the carrier frequency. To prevent mutual interference, two radar stations operate at different carrier frequencies in a full monostatic mode. Both the transmitting and receiving antennas are horn antennas with low backlobe gain, effectively reducing interference from the rear.

During the experiment, a human subject enters the room through the door, turns left at the corner, and then returns to sit on a chair placed at the center of the room. The trajectory of the human subject is illustrated in Fig. 2.

The Doppler-Time map at station 1 is illustrated in Fig. 4, obtained using a 0.5-second coherent integration time with a 0.05-second sliding window. The corresponding range result at each radar station is derived by selecting five Doppler bins with peak power using dual-frequency ranging method. The

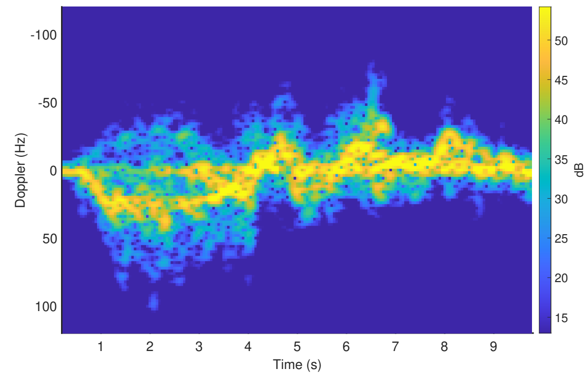

Fig. 4. Doppler-Time map at station #2

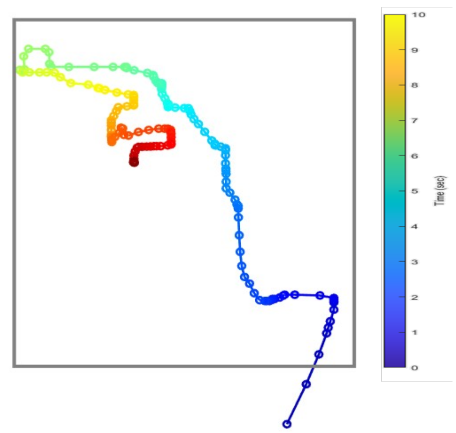

Fig. 5. Localization result for a person moving in a room

localization results over time, illustrated in Fig. 5, align closely with the actual moving trajectory depicted in Fig. 2.

V. CONCLUSION

We propose a two-radar system for through-wall human motion sensing and localization. Our dual-frequency ranging and noncoherent trilateration methods provide accurate localization while maintaining system simplicity. Experimental results confirm the effectiveness of the proposed system. Future work will focus on real-time implementation and extended coverage.

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