High-resolution Imaging and Identification of Multiple Pedestrians Using UWB Doppler Radar Interferometry and Adaptive Array Processing

Motoshi Anabuki[1], Shigeaki Okumura[1], Takuya Sakamoto[1, 2], Kenshi Saho[3], Toru Sato[1], Mototaka Yoshioka[4], Kenichi Inoue[5], Takeshi Fukuda[5], and Hiroyuki Sakai[5]
[1] Graduate School of Informatics, Kyoto University
Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan
[2] Graduate School of Engineering, University of Hyogo
2167 Shosha, Himeji, Hyogo 671-2280, Japan
[3] College of Science and Engineering, Ritsumeikan University
1-1-1 Noji-Higashi, Kusatsu, Shiga 525-8577, Japan
[4] Interactive AI Research Group, Advanced Research Division, Panasonic Corporation
Hikaridai 3-4, Seika-cho, Souraku-gun, Kyoto 619-0237, Japan
[5] Sensing Technology Research Group, Advanced Research Division, Panasonic Corporation
Hikaridai 3-4, Seika-cho, Souraku-gun, Kyoto 619-0237, Japan

***Abstract* - Imaging of the human body using ultra-wideband (UWB) radar for security applications has numerous advantages over other approaches. Recently, low-cost radar systems have been intensively studied for this purpose, employing Doppler interferometry technology to image a single human target. The technique, however, has limitations when there is more than one target person in the scene. To resolve this problem, we combined the Doppler interferometry algorithm with adaptive array processing. This approach enables the separation of multiple human targets with the help of a clustering algorithm. We applied the proposed method to simulated data and demonstrated that it could separate multiple human echoes with a root-mean-square error of 4.3 cm, which makes the accuracy more than three times higher than that of the conventional method.**

***Index Terms* —ultra wideband radar, Doppler radar, adaptive signal processing, high-resolution imaging.**

1. Introduction

Ultra-wideband (UWB) radar imaging has been applied to various applications, including monitoring human activity for security systems and pedestrian tracking for intelligent transport systems. Cameras are more commonly used, but they do not work when their vision is compromised by dust or smoke, whereas UWB radar can work in such adverse conditions.

Recently, a radar imaging technique that uses only a few antennas has been intensively studied [1]. The principle of this technique is Doppler radar interferometry, which can produce high-quality radar images when there is only a single human target [2]. The technique, however, suffers from severe image artifacts when there are multiple human targets in the same range bin at the same time.

In this paper, we propose a radar imaging system that resolves this problem, and requires only a small number of array elements. The proposed system uses 16-element antenna arrays, and combines the Doppler interferometry algorithm and adaptive array processing. Moreover, to separate multiple human targets in the generated image, we apply a clustering algorithm to automatically identify which image point belongs to which person. The proposed method is evaluated using realistic numerical simulations that employ the actual motion captured data from tracking the markers attached on a participant's body who was instructed to walk straight toward the antennas.

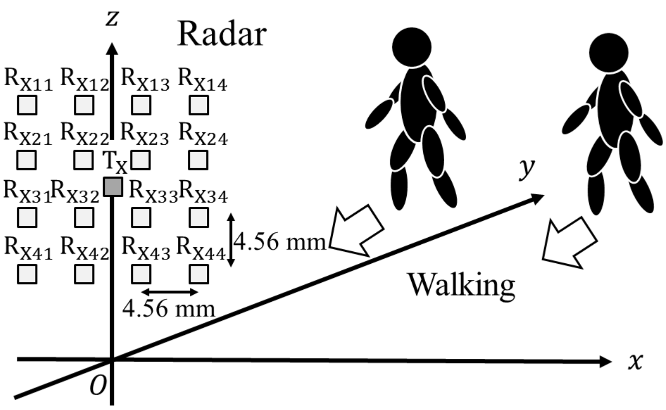


Fig. 1. System model.

2. System Model

We assume an antenna array and two human targets as shown in Fig. 1. The transmitted signal is a UWB signal that has a center frequency $f_0 = 60.5$ GHz. The wavelength at the center frequency λ is 4.96 mm. The bandwidth is $W = 1.25$ GHz, which corresponds to a downrange resolution of $\Delta r = c/2W = 12.0$ cm, where c is the speed of light. A transmitting antenna, T_X, and 16 receiving antennas, R_{X11} to R_{X44} are set up on the *x*-*z* plane. T_X is located at the central position $(0, 0, z_c)$, where $z_c = 1$ m. The interval between the receiving antennas is 4.56 mm. The pulse repetition interval, ΔT, is 0.457 ms.

3. Materials and Methods

(1) UWB Doppler interferometry

The UWB Doppler radar imaging algorithm separates multiple scattering points in the Doppler velocity domain using a short time Fourier transform (STFT), and estimates the position of each of the separated points using interferometry [2].

(2) DOA Estimation Using Capon Method

To separate targets with similar Doppler velocities, we applied the Capon method to the signal after STFT. The Capon method then estimates the DOAs by minimizing the output power under a constraint condition that maintains the echo from the desired angle [3].

The output power P_{out} using the Capon method is calculated as follows:

$$\min_{\boldsymbol{w}}(P_{\mathrm{out}} = \frac{1}{2}\boldsymbol{w}^{\mathrm{H}}\mathrm{R}_{XX}\boldsymbol{w}) \quad \text{subject to } \boldsymbol{a}^{\mathrm{T}}(\theta)\boldsymbol{w}^{*} = 1, \tag{1}$$

where $\boldsymbol{w}$ is a weight vector, $\boldsymbol{a}(\theta)$ is a steering vector, and R_{XX} is a covariance matrix of received signal data that represents the correlation of received signals. The problem can then be solved by the application of Lagrange multiplier methods. The output power of a signal from direction θ is given by:

$$P_{\mathrm{out}}(\theta) = \frac{1}{2}\boldsymbol{w}^{\mathrm{H}}\mathrm{R}_{XX}\boldsymbol{w} = \frac{1}{2\boldsymbol{a}^{\mathrm{H}}(\theta)\mathrm{R}_{XX}^{-1}\boldsymbol{a}(\theta)}. \tag{2}$$

We then estimate the DOAs by searching for the direction θ at which $P_{\mathrm{out}}(\theta)$ is a maximum.

(3) Clustering and Separation Using DBSCAN

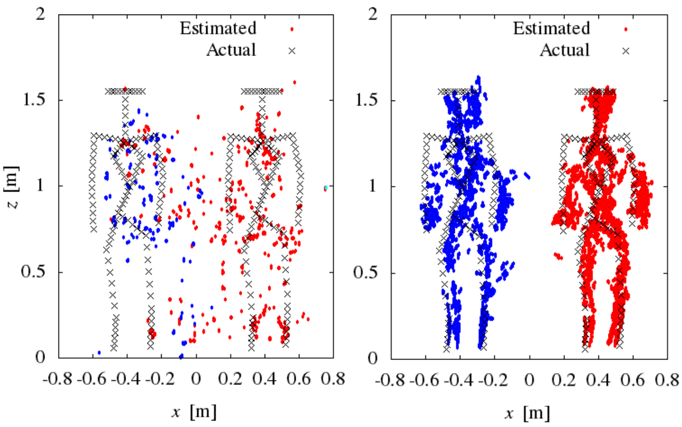
To separate and discriminate pedestrians, we applied DBSCAN, which is a data clustering algorithm [4], in t-x-y space. The procedure of DBSCAN is as follows. First, $\boldsymbol{x}$, which is one of the estimated scattering points, is randomly selected. Second, $N(\boldsymbol{x})$, which is a set of points within D-proximity of $\boldsymbol{x}$, is calculated. Then, $\boldsymbol{y}$ is classified as a density-reachable point and is included in the same cluster as $\boldsymbol{x}$, if $\boldsymbol{y}$ satisfies the following:

$$\boldsymbol{y} \in N(\boldsymbol{x}), \quad |N(\boldsymbol{x})| \geq N_{\mathrm{min}}, \tag{3}$$

where N_{min} is the threshold of the number of points. These two steps are repeated until all the density-reachable points are included in the cluster.

4. Results

We examined the performance of the proposed algorithm using numerical simulations. The received signals are calculated by ray-tracing methods with the scattering points acquired by the action data of pedestrian by motion capture. In the simulation, we assumed that two pedestrians were walking side by side with an interval of 40 cm.



(a) Conventional method (b) Proposed method

Fig. 2. Frontal view of the estimated image.

We used the root mean square error (RMSE) between the actual scattering positions and the estimated scattering positions as an evaluation index for imaging accuracy.

Fig. 2 shows the images that are generated using UWB Doppler radar interferometry and the proposed method. The colors of the points show the labels attached by DBSCAN. As shown in Fig. 2(a), the conventional method shows multiple false images present and failed to identify the pedestrians. The RMSE was 13 cm, and the number of estimated scattering points was 1410.

Conversely, the proposed method succeeded in identifying the pedestrians, as shown in Fig. 2(b). The RMSE was 4.3 cm, and the number of estimated points was 47644. When compared with the image that was acquired using the conventional method, the RMSE was improved by 67%.

5. Conclusion

We proposed a new UWB radar imaging algorithm that employs the UWB Doppler radar interferometry technique, adaptive array processing, and DBSCAN. Next, we evaluated the imaging accuracy of the proposed method through numerical simulations. The proposed method generated clear images with RMSE of 4.3 cm , and accurately identified two pedestrians. These results show that the proposed method might be effective for security applications.

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