Frequency-Domain Interferometric Imaging and Velocity Vector Estimation using Networked Ultra-wideband 80-GHz Array Radar Systems

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***Abstract*—For tracking multiple moving targets, a multi-radar system employing ultra-wideband millimeter-wave array antennas is introduced. To separate the multiple echoes and the different Doppler velocities of the targets, the frequency-domain interferometric technique is used and is followed by an interferometric imaging process. The system consists of multiple radar modules that are well-separated, allowing measurements of the Doppler velocities from different lines of sight. Thus, in addition to constructing high-resolution images, the multi-radar system is able to estimate the velocity vector of each target, which has been demonstrated in practice through measurements.**

I. Introduction

Ultra-wideband millimeter-wave radar has been of great interest in various security applications. In such applications, it is important to estimate the position and velocity of moving targets such as pedestrians. Nevertheless, the number of antennas is limited because of system costs, and the frequency band is restricted by regulations, resulting in insufficient spatial resolutions for near-field imaging. To resolve the problem, frequency-domain interferometric imaging has been studied intensively [1], [2], [3], [4]. For example, [3] uses a single 26.4-GHz three-element ultra-wideband array radar system. However, their system obtains only Doppler velocities, but not actual velocity estimates. To overcome the limitation, this study introduces a multi-radar system consisting of a pair of 80-GHz ultra-wideband array radar systems. This system estimates not only positions but also actual velocity vectors of targets even if targets are in close proximity. This system has been verified in actual measurements.

II. System Model and Measurement Setup

We use a pair of radar modules both located on a baseline, designated the x-axis, 0.9 m apart facing the same direction, the y-axis (Fig. 1). Located 1.41 m from the baseline is a rotating table, of rotation radius 0.12 m with two metallic cylinders placed vertically on top at included angle of 120° with respect to the axis of rotation. The radius and height of the target cylinders are 0.03 m and 0.3 m. The table rotates clockwise at 45 rpm, corresponding to a period of 1.33 s per revolution.

Each radar module has a transmitting antenna and four receiving antennas operating at 80 GHz. The polarization of the antennas is vertical. The receiving antennas form a linear horizontal array with a spacing of 1.9 mm corresponding to half the wavelength ($\lambda/2$), resulting in an array aperture of 5.7 mm (1.5λ). The transmitting signals are code-modulated at a D/A rate of 2.0 GS/s, resulting in 3-dB bandwidth of 1.0 GHz, which corresponds to a range resolution of 150.0 mm. The signal received at each of the array antennas is sampled at 2.0 GS/s, corresponding to a range bin of 75.0 mm.

III. Frequency-Domain Interferometry and Estimation of Location and Velocity Vector of Multiple Targets

We define $s_{i,j}(t,\tau)$ $(i=\{1,2\})$ $(j=\{1,2,3,4\})$ as the signal received at the j-th element of module i, where t and τ are slow and fast times, respectively. Frequency-domain interferometry separates multiple targets moving at different line-of-sight velocities in the frequency domain as

$$S_{i,j}(t,\omega,\tau)=\int s_{i,j}(t',\tau)w(t'-t)\mathrm{e}^{-\mathrm{j}\omega t'}\mathrm{d}t', \qquad (1)$$

where w is a window function; for this study, we used a Hann window.

Next, we identify peaks of the spectrogram at each slow time t to obtain the m-th Doppler angular frequency $\omega_i^{(m)}(t)$ and fast time $\tau_i^{(m)}(t)$, and estimate the direction-of-arrival (DOA) $\theta_i(t,\omega_i(t),\tau_i(t))$ from the interferometric analysis,

$$\theta_i(t)=\sin^{-1}\left(\angle\left(S_{i,2}(t,\omega_i,\tau_i)-\angle S_{i,3}(t,\omega_i,\tau_i)\right)/kd\right), \qquad (2)$$

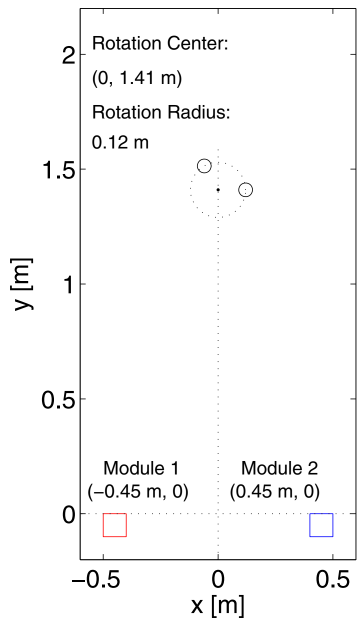

Fig. 1. Measurement setup with two radar modules and a rotating table.

where $k = 2\pi/\lambda$ is a wave number.

The range of the target, or time of arrival (TOA), can be estimated using the fast time at the spectrogram peaks using $\rho_i(t) = c\tau_i(t)/2$,where c is the speed of light. The target position can be estimated using the DOA $\theta_i(t)$ and TOA $\rho_i(t)$. In addition, because we have a pair of radar modules located some distance apart, the target velocity vector can be estimated by combining $\omega_1(t)$ and $\omega_2(t)$.

IV. Experimental Verification

Figure 2 shows the estimated positions and velocity vectors of the scattering centers at $t = 0$s, 0.12 s, and 0.23 s. The red and blue points are positions estimated using modules 1 and 2, respectively. The arrows are velocity vectors estimated by combining data from the two radar modules. The dashed black line is the actual target trajectory, and the black circles represent the actual target position and shape. We emphasize that at $t = 0$ the two cylindrical targets are separated by 0.1 m, which cannot be separated by range resolution only (0.15 m). The experimental results thus demonstrate the remarkable accuracy of the proposed multi-radar system operating at 80-GHz millimeter range.

V. Conclusion

We investigated the feasibility of a multi-radar system that consists of a pair of ultra-wideband millimeter-wave array radar modules. Using the frequency-domain interferometric imaging technique, we combined the Doppler velocities measured using the two radar modules and successfully estimated the target velocity vectors as well as accurate positions of the scattering centers situated closer than the range resolution.

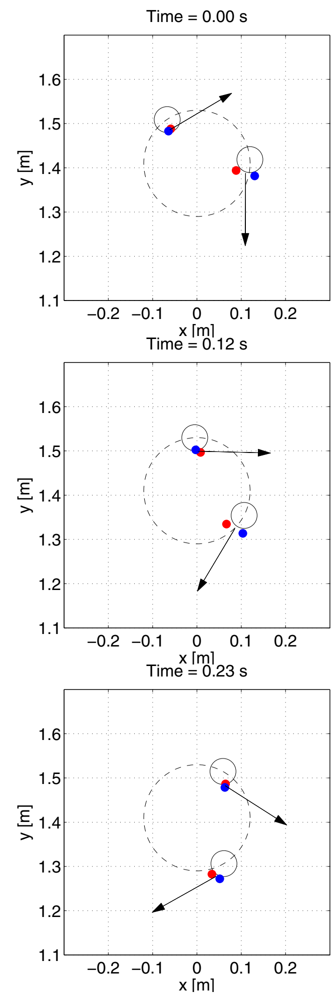

Fig. 2. Estimated positions and velocity vectors of scattering centers using the proposed method.

Acknowledgment

This study was supported in part by the Kyoto University SPIRITS project, the Center of Innovation (COI) Program, JSPS KAKENHI (Grant Nos. 25249057, 15K18077, and 15KK0243), and the "R&D project for expansion of radio spectrum resources for more efficient use of frequency resources for the future" (The Ministry of Internal Affairs and Communications, Japan).

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