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High-resolution UWB Doppler radar interferometric imaging algorithm for multiple moving targets with smoothed pseudo Wigner distribution

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Abstract This study proposes high-resolution UWB (Ultra Wide-Band) Doppler radar imaging algorithm with a small number of antennas. Targets are resolved first in a range direction using smoothed pseudo Wigner distribution, and then in angular directions with interferometry. As a result of performance evaluation with numerical simulations and experiments, the proposed algorithm achieves high-resolution imaging for multiple moving targets. The mean error of the estimated image is 5.2mm, which corresponds to 1/58 of the nominal resolution determined by the bandwidth.

Key words UWB Doppler radar, high-resolution imaging, interferometry, smoothed pseudo wigner distribution

1. Introduction

Due to the increase of crime and terrorism in recent years, surveillance systems are important in our society. For these systems, accurate detection of moving targets has become a topic of interest. Although cameras have been applied for such applications, their sensitivity is insufficient in conditions where light is poor, and thier resolution is insufficient [1], [2]. To avoid these problems, radar systems have been studied, and have realized detection of intruders [3]– [5]. However, these systems estimate only meter order position, and do not provide the shape information. For shape estimation of moving targets, inverse synthetic aperture radar systems have been proposed [6], [7], however these are time-consuming with inadequate resolution.

As a solution for these problems, UWB (Ultra Wide-Band) radar is an efficient tool because of its high-resolution capability. SEABED (Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves) is known as fast and high-resolution imaging algorithm for UWB radar [8]. Although SEABED developed for fixed target, this algorithm has extended to moving target, and achieves high-resolution imaging with small number of fixed antennas [9], [10]. However, these algorithms considered single target, thus it is difficult to apply for multiple targets.

To detect the multiple moving targets, Lin and Ling [11]–[13] have proposed the interferometric imaging algorithm with CW (Continuous Wave) Doppler radar. This algorithm separates the multiple targets utilizing difference of their Doppler frequency, and extracts direction-of-arrival (DOA) of each target with the interferometry. However, range resolution is insufficient because of using CW radar. Additionally, there are incorrect detections due to the variation of Doppler frequency.

This paper describes a high-resolution imaging algorithm for multiple moving targets with UWB Doppler radar. We propose the utilization of smoothed pseudo Wigner distribution (SPWD) for separation of the targets. SPWD generates high-resolution time-frequency distribution [14], [15], and can separate multiple moving targets accurately. Additionally, we propose a target shape estimation algorithm with SPWD and the interferometry. The proposed algorithm estimates the orbit of scattering centers for each target separated by SPWD, and compensates for the motion of the target on the acquired orbit of scattering centers. The performance evaluation with numerical simulations and experiments verify that the proposed algorithm achieves high-resolution imaging for multiple moving targets having time-varying Doppler

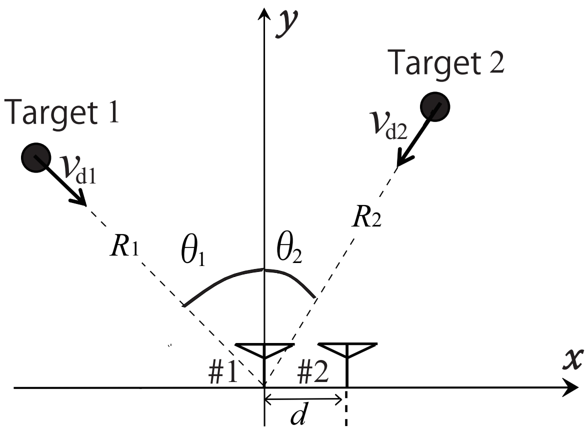

Fig. 1 System model.

frequency.

2. Conventional Interferometric Imaging Algorithm

Fig. 1 shows the system model. For simplicity, we deal with 2-dimensional problems in this paper. The positions of antennas #1 and #2 are (0, 0) and (d, 0), respectively. Transmitting signal is CW whose wavelength is λ. The conventional algorithm is composed of separation of multiple targets with Fourier transform and DOA estimation with an interferometry [11], [12]. The received signals after applying Fourier transform of antenna #1 and #2 are $F_1(f)$ and $F_2(f)$, respectively. If different moving targets have different radial velocity, we can separate these targets with the spectrum by the deference of their Doppler frequency. The Doppler frequency of target n is expressed as

$$f_{\mathrm{d}n} = \frac{2v_{\mathrm{d}n}}{\lambda}, \tag{1}$$

where $v_{\mathrm{d}n}$ is the radial velocity of target n. Then, the DOA of each target is calculated by phase difference between two antennas at each Dopppler frequency component. This DOA estimation method is known as interferometry. In interferometry with a couple of antennas, DOA of target n is calculated as

$$\theta_n = \sin^{-1}\left[\frac{\angle F_1(f_{\mathrm{d}n}) - \angle F_2(f_{\mathrm{d}n})}{(2\pi d/\lambda)}\right]. \tag{2}$$

In addition, target range R_n can be calculated by the frequency domain interferometry with two CW frequencies [13]. With the estimated θ_n and R_n, the conventional algorithm can derive the three-dimensional locations of multiple moving targets with a small number of antennas [11]–[13].

However, the conventional algorithm fails target separation where the targets have time-varying radial velocity. An example of the Doppler spectrum of the conventional algorithm follows. Three rotational targets are assumed. An angular velocity of targets is 1.5π rad/s. The inter pulse period (IPP) and the observing time are 1.29msec and 1.32sec, respectively. In this condition, the targets rotate a round during the observing time. The received signals are calculated with ray-tracing. Fig. 2 shows the targets and the estimated spectrum of antenna #1. Although the number of targets is three, the number of peaks exceeds three. These false peaks are detected by the radial velocity variation of the targets, thus the conventional algorithm is not applicable in practical environments.

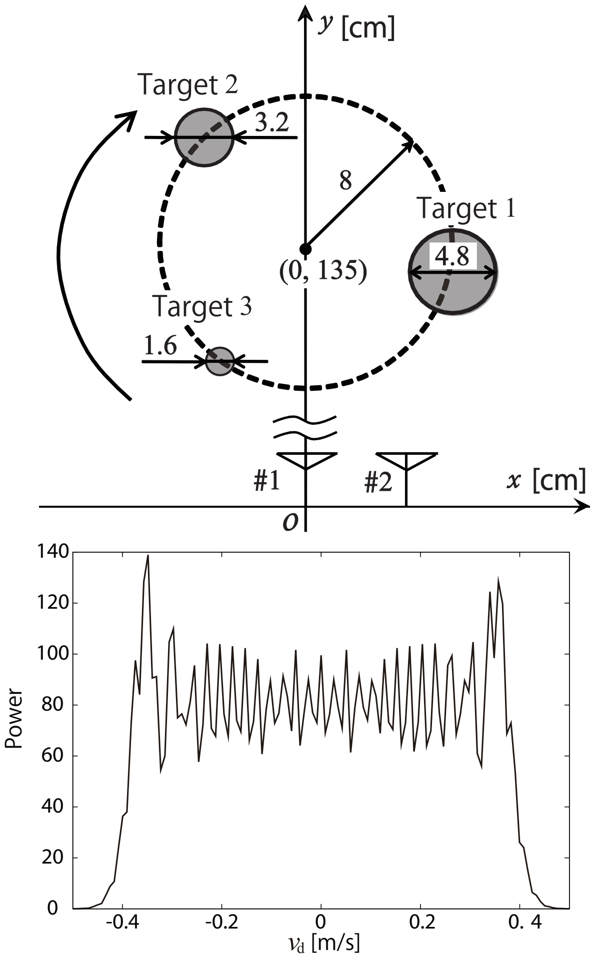

Fig. 2 Assumed rotational targets (above) and the spectrum of #1 estimated by conventional method (below).

3. Proposed Imaging Algorithm

To resolve the problem described in the previous section, we propose a high-resolution imaging algorithm with UWB Doppler radar and SPWD. Using UWB Doppler radar, we can obtain the range information. SPWD is one of the time-frequency analysis method, and possesses a high-resolution in the time-frequency plane compared with other method such as short time Fourier transform [14], [15]. In the proposed algorithm, multiple moving targets are resolved in a range direction by using UWB radar and time-frequency dis-

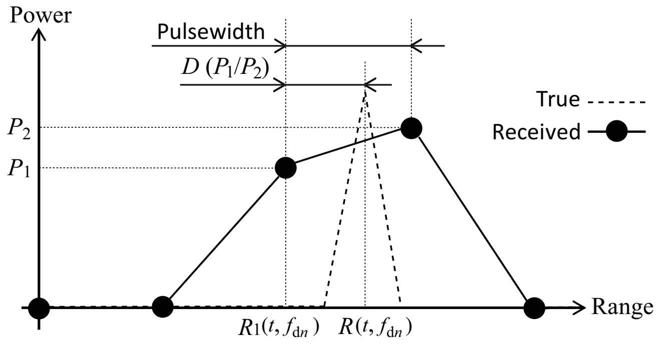

Fig. 3 An example of recieved signal and true distance.

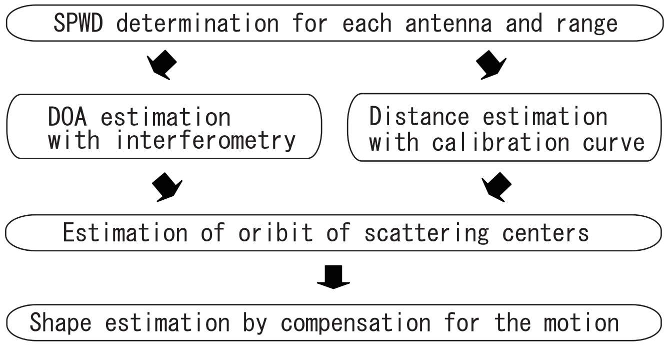

Fig. 4 Procedure of the proposed algorithm.

tribution estimated with SPWD. We assume that the system model is same as Fig.1. First, we acquire the received signal $r_{ij}(t)$ in each antenna i and range j. SPWD is obtained by smoothing of Wigner distribution which generates the spectrum for each time [15]. Wigner distribution of $r_{ij}(t)$ is given by

$$W_{ij}(t, f) = \int r_{ij}(t+\tau/2) r_{ij}^*(t-\tau/2) \exp(-j2\pi f\tau) d\tau, \quad (3)$$

where * means complex conjugate. SPWD of $r_{ij}(t)$ is estimated with $W_{ij}(t)$ as

$$S_{ij}(t, f) = \int\int \Phi(t-t', f-f') W_{ij}(t', f') dt' df', \quad (4)$$

where $\Phi(t, f)$ is a smoothing function. The proposed algorithm uses the 2-dimensional Gaussian function for $\Phi(t, f)$ which is expressed as

$$\Phi(t, f) = \exp\left(-\frac{t^2}{\alpha^2}\right) \exp\left(-\frac{4\pi^2 f^2}{\beta^2}\right), \quad (5)$$

where α and β are correlation length of Gaussian function. As expressed in Eq. (4), SPWD estimates the Doppler spectrum for each time and range. Therefore, accurate separation is realized even in the targets having time-varying Doppler frequency.

Furthermore, we propose a target shape estimation algorithm with SPWD and the interferometry. As described in above, high-resolution time-frequency distribution is acquired with SPWD. Then, we can estimate the orbit of the scattering centers by mapping its $t-f$ on a plane of distance and DOA. The DOA $\theta(t, f_{\mathrm{d}n})$ is estimated with the interferometry same as Eq. (2). The distance $R(t, f_{\mathrm{d}n})$ is estimated by peak extraction in range direction. However, to realize the high-resolution imaging, it is necessary to estimate distance in the accuracy below the range resolution. For this purpose, the proposed algorithm utilizes the calibration curve which expresses the relationship between signal power and the distance. Fig. 3 shows an example of received signal and true distance $R(t, f_{\mathrm{d}n})$. We prepare the calibration curve $D(P_1/P_2)$ in advance. We extract the maximum power and the second maximum power, and define P_1 and P_2 as these powers from the smaller range. As shown in Fig. 3, $R(t, f_{\mathrm{d}n})$ is estimated with $D(P1/P2)$ and the range $R_1(t, f_{\mathrm{d}n})$ corresponding to P_1 as follows:

$$R(t, f_{\mathrm{d}n}) = R_1(t, f_{\mathrm{d}n}) + D(P_1/P_2). \quad (6)$$

With obtained $R(t, f_{\mathrm{d}n})$ and $\theta(t, f_{\mathrm{d}n})$, the orbit of scattering centers are determined by

$$\begin{cases} x(t, f_{\mathrm{d}n}) = R(t, f_{\mathrm{d}n}) \sin[\theta(t, f_{\mathrm{d}n})] \\ y(t, f_{\mathrm{d}n}) = R(t, f_{\mathrm{d}n}) \cos[\theta(t, f_{\mathrm{d}n})]. \end{cases} \quad (7)$$

Finally, the proposed shape estimation algorithm compensates for the motion of the target on the acquired orbit of scattering centers.

The procedure of the proposed algorithm is summarized in Fig. 4. The proposed algorithm realizes not only accurate separation of multiple targets, but also the high-resolution shape estimation of all targets. Moreover, we can estimate two-dimensional image with only two antennas. For simplicity, this paper assumes that the motion of targets is known.

4. Performance Evaluation with Numerical Simulation

This section shows targets separation and shape estimation examples with the proposed algorithm in numerical simulation. We utilize a UWB pulse with carrier frequency of 26.4GHz and range resolution of 30cm. α=3Δt and β=4Δf are set, where Δt and Δf are the IPP and the frequency resolution, respectively. The antennas are omni-derectional, and their separation d is 5cm. The targets, IPP, and observing time are same as in Sec. 2.

The true radial velocity of the targets and the SPWD spectrograms are shown in Figs. 5 and 6, respectively. The targets exist in between range 4 and 5 in this condition, thus we show the spectrograms $S_{14}(t, v_{\mathrm{d}})$ and $S_{15}(t, v_{\mathrm{d}})$. It can be seen that SPWD detects the time-varying radial velocity of all targets accurately. Comparing with the spectrum shown in Fig. 2, the proposed algorithm achieves accurate separation even in the case that the conventional algorithm cannot

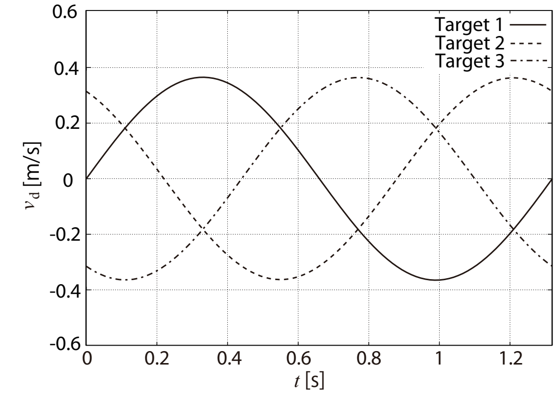

Fig. 5 True radial velocity of the three rotational targets.

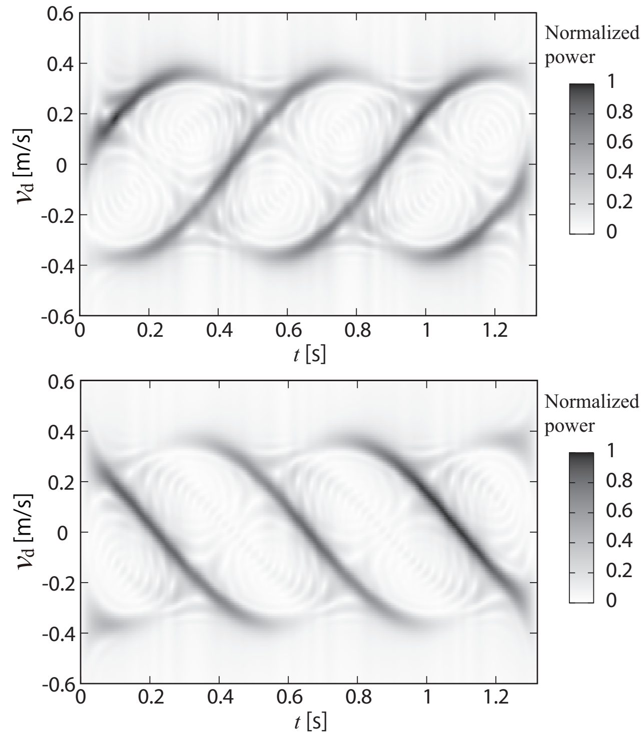

Fig. 6 SPWD spectrogram of #1 in range 4(below) and 5(above).

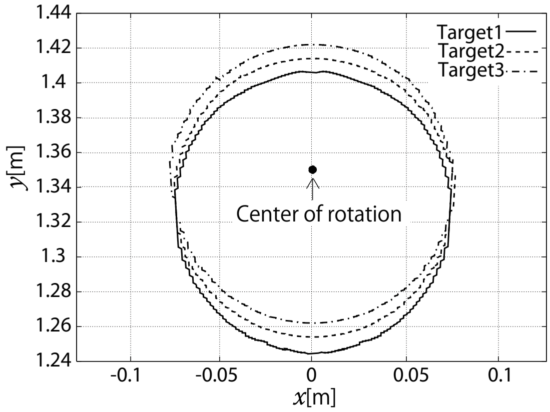

Fig. 7 Estimated orbit of scattering centers.

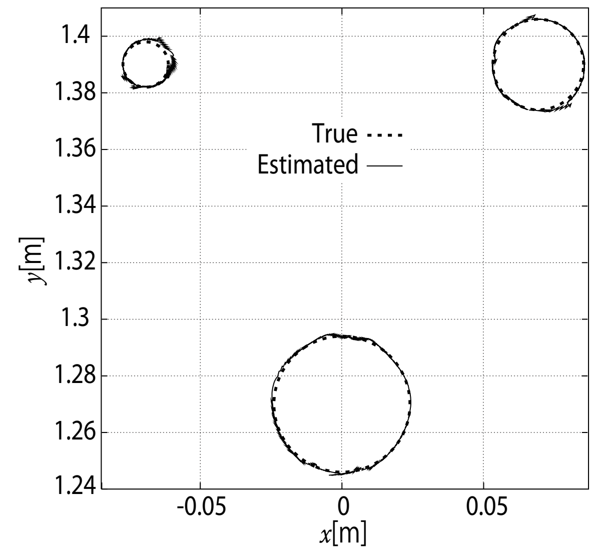

Fig. 8 Estimated image with proposed algorithm.

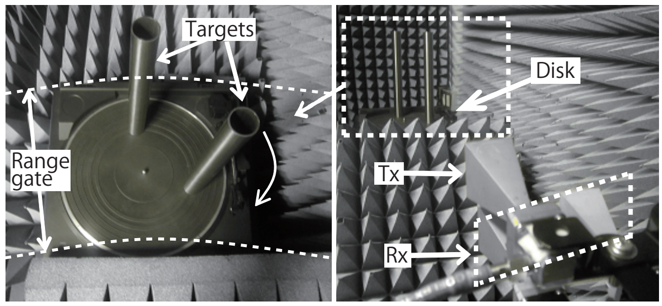

Fig. 9 Experimental site.

detect the targets. Fig. 7 shows the orbit of scattering centers estimated with obtained SPWD. This figure shows that accurate locations of the scattering centers for each target are estimated. Fig. 8 shows the estimated image with compensation for the rotation. As shown in this figure, high-resolution shape estimation of all targets is realized. The mean error of estimated image is 0.35mm. These results indicate that the proposed algorithm realizes accurate separation of multiple moving targets, and achieves high-resolution imaging for all targets.

5. Performance Evaluation with Experiment

This section investigates the performance of the proposed algorithm with experimental data. Fig. 9 shows the experimental site. We assume two rotational circle targets made of stainless whose radius is 3.3cm. The rotational center is (0, 1.3m), the distance between rotational center and center of the targets is 8cm, and angular velocity is 1.5π rad/s. We use a transmitting antenna and two receiving antennas. The transmitting pulse and location of the receiving antennas are same as in the previous section. The 3-dB beamwidth of the antenna is 23.2°.

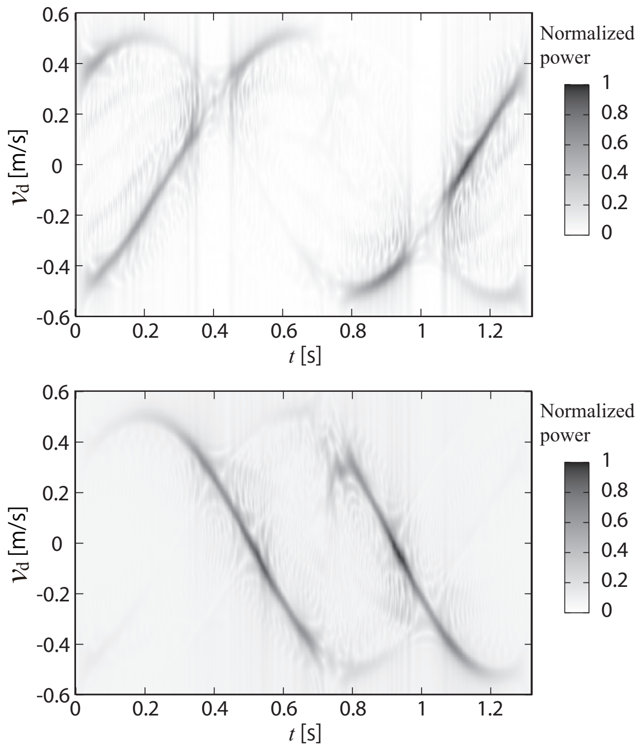

Fig. 10 SPWD spectrogram #1 in range 4(below) and 5(above) in the experiment.

Fig. 10 shows the spectrograms $S_{14}(t, v_d)$ and $S_{15}(t, v_d)$. This figure proves that SPWD accurately separates the multiple targets even in a real environment. Fig. 11 shows the estimated scattering centers. The estimated orbit of scattering centers is distorted because of the interference of the targets. To remove these erroneous points, we use only the points whose S/N is relatively high for shape estimation. Fig. 12 shows the estimated image with the proposed algorithm. This figure proves that the proposed algorithm estimates high-resolution image of both targets. The mean error of the estimated image is 5.2mm which corresponds to 1/58 of the nominal resolution determined by the bandwidth.

6. Conclusion

This paper proposed a high-resolution imaging algorithm for multiple moving targets with UWB Doppler radar. The proposed algorithm utilizes SPWD for multiple targets separation, and estimates the shape of each target with interferometry and motion compensation. In a numerical simulation, we showed that the proposed algorithm realizes accurate separation of multiple moving targets. Additionally, our algorithm estimated high-resolution image of all targets. We also showed application example with experimental data. The results of the experiment verified that the proposed algorithm achieves high-resolution imaging for multiple moving targets even in a real environment. The mean error of the estimated image is 5.2mm, which corresponds to 1/58 of the nominal resolution determined by the bandwidth. However, these investigations assumed that the motion of the targets is known, thus developing of a motion estimation method is our important future work.

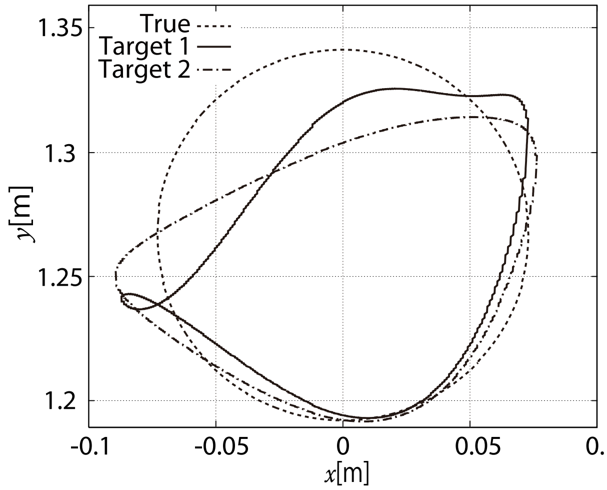

Fig. 11 Estimated orbit of scattering centers in the experiment.

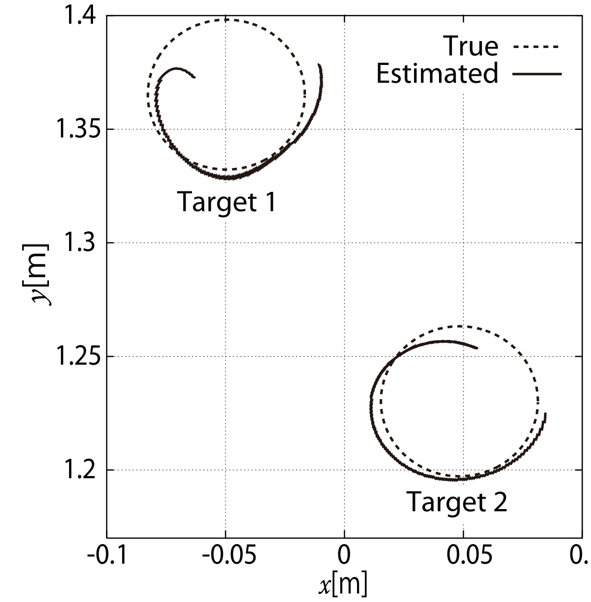

Fig. 12 Estimated image with the proposed algorithm in the experiment.

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