Corner target positioning with unknown walls' positions

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Abstract: Here we consider a corner target positioning problem under the condition of unknown walls' positions using time-division multiple-input-multiple-output (MIMO) radar. Firstly, we propose an estimation algorithm for the walls' positions using the Back-Projection (BP) imaging algorithm. Then, after obtaining the BP image of target, we extract the focus regions formed by the reflections and the diffractions. Finally, we obtain the position of the target based on the extracted walls' positions and the focus regions. Simulations and experiments results validate the proposed algorithm.

1 Introduction

Positioning of a hidden target in a corner is important in various applications, such as urban battles, rescues, and antiterrorism [1, 2]. Due to the obstacle of walls, the electromagnetic (EM) wave is not able to reach the corner hiding target along the line of sight (LOS) path and may propagate along the multiple non-LOS (NLOS) paths, yielding multipaths. As such, these multipaths can be exploited to detect the hidden target in a corner.

Many works have been exploited the multipath to detect hidden targets [2–9]. In [2], the Range-Doppler image was generated to show the discrimination of moving targets by using multipath in LOS and NLOS situations. Additionally, the multipath was also exploited to obtain micro-Doppler features from moving humans in [3, 4]. However, these models cannot extract the target's positions.

Many signal-processing techniques have been developed to get the position of the hidden targets [5–12]. In [5], the authors utilised composite point spread function and point spread function to image a hidden target accurately based on synthetic aperture radar. In [6], the authors proposed a target positioning method based on the multipaths formed by the reflections and the diffractions. In [7], matched subspace filter approach was developed to locate the targets hidden in a corner. However, these techniques use the assumption of known walls' positions in priority. In practice, the relative positions between radar and walls are generally unknown, leading to an error for targets' positioning.

In this paper, we consider a corner target positioning problem under the condition of unknown walls' positions. Firstly, a novel estimation algorithm for the walls' positions is proposed. Then, we extract the focus regions after obtaining the BP image of the target. Finally, the technique of double elliptical localisation [8] is used to obtain the target's position based on the extracted walls' positions and the centroid of the focus regions.

The rest of the paper is organised as follows: In Section 2, we analyse the EM wave propagation model in the corner and review the principle of BP imaging algorithm. In Section 3, the estimation algorithm for the walls' positions and the target positioning method are discussed. In Section 4, simulations and experiments validate the proposed algorithm. Section 5 concludes this paper.

2 Signal model

Consider a point-like target \( P \), located at \((x_P, y_P)\), hiding behind a corner \( C \) at \((x, y)\), formed by Wall-1 and Wall-3 as shown in Fig. 1. Wall-2 is placed parallel to Wall-1 with the distance of \( D_1 - D_2 \). A time-division MIMO [13] radar is employed with \( M \) radiating antennas and \( N \) receiving antennas. The antennas array is placed with angle \( \beta \) with respect to Wall-3.

Suppose the \( n \)-th transmitting antenna, located at \((x_{nm}, y_{nm})\) radiates signal \( s(t) \), the echoes received by the \( n \)-th receiving antenna, located at \((x_{nm}, y_{nm})\), is expressed as

\[
y_{nm}(t) = \sum_{l=1}^{2} \sigma_{nl} s_{nl}(t - \tau_{nm}^l) + \xi(t)
\]

(1)

where \( \xi(t) \) is the noise, \( \tau_{nm}^l \) denotes the round-trip delay between radar and the target through the \( l \)-th path, \( \sigma_{nl} \) is the backscattering coefficient of the \( l \)-th path. Since the existence of the corner and multiple walls, the signal may propagate along the following paths:

(1) Path-I: The signal propagates by a specular reflection on Wall-2.
(2) Path-II: The signal propagates by a specular reflection on Wall-2 and a specular reflection on Wall-1.

Paths propagated by three or more reflections are omitted owing to the severe attenuation. Besides, path propagated by diffraction is too weak to be considered.

Because both of the radiated signal and the receiving signal may pass by these two paths, the echo in (1) can be rewritten as

\[
y_{nm}(t) = \sum_{l_1=1}^{2} \sum_{l_2=1}^{2} \sigma_{nl_1} \sigma_{nl_2} s_{nl_1}(t - \tau_{nm}^{l_1}) + \xi(t)
\]

(2)

Fig. 1 Multipath propagation model
where \( \tau_{\text{min}}^{(l)} \) denotes the round-trip delay for the paths combined with the \( l \)th transmit path and the \( l \)th receive path. \( \sigma_{\text{min}}^{(l)} \) is the backscattering coefficient for the paths combined with the \( l \)th transmit path and the \( l \)th receive path.

Let \( r_{\text{m}} \) denotes the propagation delay between the \( m \)th transmitter and the target, expressed as

\[
r_{\text{m}} = \frac{1}{c} \sqrt{(x_{\text{m}} - x_{\text{t}})^2 + (y_{\text{m}} - y_{\text{t}})^2}, \quad l = 1, 2
\]

where \( c \) represents the velocity of EM wave in the air, \((x_{\text{t}}, y_{\text{t}})\) denotes the coordinates of the virtual target produced by Path - I and Path - II, given by

\[
\begin{align*}
x_v &= \frac{2D_2 - x_{\text{p}}} {2D_2 - 2D_1 + x_{\text{p}}} \quad v = 1 \\
y_v &= y_{\text{p}} \quad v = 1, 2
\end{align*}
\]

where \( v = 1 \) denotes the virtual target \( P' \) and \( v = 2 \) denotes the virtual target \( P'' \) as shown in Fig. 1.

Similarly, \( r_{\text{m}} \) denotes the propagation delay between \( m \)th receiver and the target, which is expressed as

\[
r_{\text{m}} = \frac{1}{c} \sqrt{(x_{\text{m}} - x_{\text{t}})^2 + (y_{\text{m}} - y_{\text{t}})^2}, \quad l = 1, 2
\]

Thus, the round-trip propagation delay \( \tau_{\text{m}}^{(l)} \) is expressed as

\[
\tau_{\text{m}}^{(l)} = r_{\text{m}} + r_{\text{m}}
\]

As such, the scenario shown in Fig. 1 can be imaged by BP imaging algorithm. By discretising the region of imaging into \( N_x \times N_y \) pixels, the image \( I_{\text{BP}} \) can be obtained, which is expressed as

\[
I_{\text{BP}} = \{ I_{\text{BP}}^{(l)}, \quad k = 1, 2, \ldots, N_x \times N_y \}
\]

where \( I_{\text{BP}}^{(l)} \) is the value of the \( k \)th pixel, denoted as

\[
I_{\text{BP}}^{(k)} = \sum_{m=1}^M \sum_{l=1}^N \sigma_{\text{min}}^{(l)} + r_{\text{m}}^{(l)}
\]

where \( r_{\text{m}}^{(l)} \) is the round-trip delay between the pixel \( x_{\text{m}} \) and the \( m \)th transmitting antenna as well as the \( m \)th receiving antenna.

In practice, the walls' positions \( D_1 \) and \( D_2 \) that used in (4) are generally unknown, which are important on target localisation. As such, in the next section, we first propose an estimation algorithm for the walls’ positions. Then, we describe the target positioning method.

### 3 Proposed algorithm

#### 3.1 Walls’ positions

Suppose that there are \( M \) radiating antennas and \( N \) receiving antennas, \( T_{\text{m}} \) denotes the distance between each radiating antenna \( T_{\text{m}} \) and the target \( P \), and \( L_{\text{m}, \text{p}} \) denotes the distance between each receiving antenna \( R_{\text{m}} \) and the target \( P \). Based on the principle of BP imaging algorithm, there will be \( M \times N \) ellipse locus with the focus \((T_{\text{m}} 0), (R_{\text{m}} 0), \) and the major axis \( L_{\text{m}, \text{p}} + T_{\text{m}, \text{p}} \) as the red dotted ellipse locus shown in Fig. 2. It is clear that the target focus point \( P \) appears as the overlapping region of this ellipse locus. Besides, there always appears another overlapping region \( P_1 \) at the symmetric place of the target \( P \).

Considering the feature mentioned above, we propose an estimation algorithm to obtain the position of walls. Specifically, the detailed steps are presented as follows:

### 3.2 Target positioning

For the scenario shown in Fig. 1, let \( A_l, l_1, l_2, l_1 = 1, 2; l_2 = 1, 2 \) denotes the target focus produced by the paths combined with the \( l \)th transmit path and the \( l \)th receive path.

To obtain the position of the target, we first extracted the focus regions produced by different multipaths of the BP imaging. Then, the Euclidean distance between each focus region and the array
Based on the proposed method, we obtain the extracted walls’ positions as the red lines. Fig. 5b shows the imaging result of the target. It is clear that all of the three main focus, which are produced by different paths, are derived from the real position of the target. However, based on the proposed approach, the real target’s position is extracted successfully as the red upper triangle.

In order to facilitate comparison, Table 1 lists the ground truth details of the experimental results. Compared to the simulation, the mean of the results calculated by (9)–(11) is obtained to improve the accuracy.

### 4 Numerical results

In this section, EM simulations and real data collection experiments are provided to validate the proposed method.

#### 4.1 EM simulation results

We generate the echo of one stationary point-like target in a corner using grpMAX. The target is placed at (2.0 m, 2.1 m). We use a time-division MIMO array with two transmitting antennas and four receiving antennas. Two transmitting antennas are located at both ends of the array, 3.75 cm apart from the adjacent receiving antennas, and four receiving antennas are placed at equal intervals, spaced 7.5 cm apart.

Firstly, as array A in Fig. 3, we place the array centre at (1.2343 m, 0.9343 m) with angle $\theta = 45^\circ$ to extract the position of Wall-1. Then, we rotate the array with angle $\alpha = 90^\circ$ with the array centre unchanged as array B to obtain the position of Wall-2. Based on the estimation method of walls’ positions in Section 3, we obtain the EM simulation results as shown in Fig. 5a. Two focus produced by Wall-3 and one focus produced by Wall-2 appear in the image. Based on the proposed method, we obtain the extracted walls’ positions as the red lines. Fig. 5b shows the imaging result of the target. However, based on the proposed approach, the real target’s position is extracted successfully as the red upper triangle.

In order to facilitate comparison, Table 1 lists the ground truth and the extracted results of different parameters, the errors between the two parameter are calculated with $l_2$-norm. As we can see, the maximum error is 0.056 m, which is small enough to validate the proposed method.

#### 4.2 Experimental results

The real experimental scene is shown in Fig. 6, the array centre is placed at (4 m, 2.5 m) and a person standing at (7.5 m, 10 m). Stepped frequency signal is employed as the probing signal, with the frequency range from 1.6 to 2.2 GHz. The frequency step is 2 MHz. Thus, 300 frequency measurements are collected and the range resolution is 25 cm.

Based on the proposed method, we obtain the results as shown in Fig. 7. Although there are many clutters, the focus produced by Wall-3 and Wall-2 in Fig. 7a are strong enough to be distinguished. As shown in Fig. 7b, the three main focus appear obviously. Thus, the real position of the target can be extracted successfully as the red upper triangle. Owing to the door and other things on the Wall-2, the errors are larger; however, the means of different mutipaths can be obtained to reduce the error. Table 2 lists the details of the experimental results. Compared to the simulation, the errors are larger in actual environment. However, the maximum error between the real position and the extracted result is 31.4 cm, validating the effective of the proposed method.

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Table 1 | Comparison of simulation parameters (unit in meters)  
| Parameter | $D_1$ | $D_2$ | $(x_p, y_p)$ | Errors |  
|-----------|------|------|-------------|--------|  
| ground truth | 1.8 | 2.5 | (2.0, 2.1) | |  
| extracted Results | 1.83 | 2.53 | (2.051, 2.078) | 0.03 | 0.03 | 0.056 |
5 Conclusion
This paper has addressed the corner target localisation problem under unknown walls’ positions. Based on the BP imaging algorithm, we have proposed an estimation method for the wall’s positions. By using the extracted walls’ positions, we have obtained the position of the target. Numerical results demonstrate the effectiveness of the proposed approach. Possible future work might concern the study of multi-target localisation.

6 Acknowledgments
This work was supported in part by Chang Jiang Scholar Program, in part by the National Natural Science Foundation of China under Grants nos. 61771109, 61703417, and 61501083, and in part by the 111 project No. B17008.

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