A Method of Estimating a Room Shape using a Single Antenna in a Multipath Environment

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***Abstract*—In this paper we propose a low-cost radar based indoor security system with super-resolution capability. A high-resolution imaging algorithm, the TR (Time Reversal) method, is employed to realize a simplified radar system with only a single antenna. While the TR method provides some advantages, it requires prior accurate information about the multipath environment. Since this is usually difficult to achieve in practice, we propose a new method to estimate the multipath environment without any reference targets for calibration. The proposed method makes the TR method practical and effective in estimating target location without calibration for any particular indoor environment.**

I. INTRODUCTION

With an increase in crime and acts of terrorism, indoor security systems have attracted much attention in recent years. In a multipath environment in a room, the technique super-resolution in the field of communications has been studied [1]. This technique is closely related to the concept of TR (Time Reversal) in the field of sensing. DORT (a French acronym for the decomposition of the time reversal operator) [5], [6] is a SVD (Singular Value Decomposition) based TR technique reported to have high-resolution imaging capability. In previous work, we extended the DORT method to a single antenna radar system in a multipath environment; we were able to obtain high-resolution images unachievable using conventional methods [7].

However, these high-resolution TR methods have a common serious drawback; they need accurate information about the multipath environment beforehand. This is usually difficult or time-consuming in practice. In this study, we propose a method to estimate the multipath environment using a single antenna without any reference targets for calibration. The proposed method is based on a model-fitting approach that finds the best solution that matches observed multiple scattered echoes. Furthermore, using the proposed method, we show some results of an estimated target location based on the multipath environment.

II. SYSTEM MODEL

For simplicity, electromagnetic wave propagation and room models are assumed to be 2-dimensional. The room, composed of a known material, is assumed to have an unknown polygonal shape as in Fig. 1. It is assumed that a mono-static radar system with a single omni-directional antenna is located at $(0, 0)$, an unknown position in the room. This antenna is used as a transmitter and receiver. A mono-cycle pulse with the center frequency of 1.0 GHz is transmitted from the antenna and echoes are received by the same antenna. The received signal is A/D converted and stored in memory. A filter matched to the transmitted pulse is applied to the received signal and the output $s(t)$ is obtained. Fig. 3 shows an example of the signal $s(t)$, in which we see 4 direct reflection echoes (shown by circles), which are followed by multiple scattering echoes. This signal is generated numerically by employing a ray-tracing algorithm. This study aims to estimate the shape of the room using this signal $s(t)$ under the above-mentioned conditions.

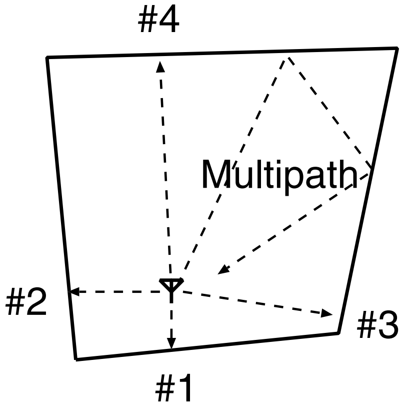

Fig. 1. The assumed system model with a single antenna in a polygonal shaped room.

III. TIME-REVERSAL IMAGING

The target location cannot be obtained by a single antenna in a free space because the radar system can estimate only the distance to the target, not the angle. By using multiple reflection echoes, however, a simple radar system with a single antenna can estimate the target position. This means that a target locating system can be realized by a low-cost practical system if it is placed in a multipath environment. Time-reversal imaging is recognized as a method that can obtain a high-resolution image unachievable by conventional methods. To apply the time-reversal imaging, a matched filter is applied to a raw signal to accurately determine the time zero $t = 0$, getting rid of an ambiguity of time translation. The TR image

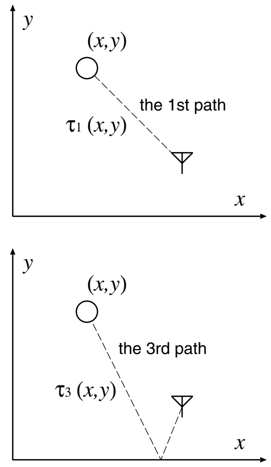

Fig. 2. Propagation paths between the antenna and the target via multiple reflections.

$I(x, y)$ is calculated as:

$$I(x,y) = \left| \sum_{i,j} f(\tau_i(x,y) + \tau_j(x,y)) \right|, \qquad (1)$$

where $f(t)$ is a matched-filtered received signal from a point-like target in a multi-path environment, and $\tau_i(x, y)$ is defined as the time delay between the antenna and the target via the i-th path.

Fig. 2 shows some of the paths between the antennas and the targets. The target location is accurately estimated by the above-mentioned method if the multipath environment is precisely known prior to the actual measurement. It is, however, time-consuming to manually measure all the walls, and this calibration process has been the most significant drawback of time-reversal imaging methods. The next section provides a new approach to solve this difficulty keeping the system simple and low-cost without using any other devices.

IV. PROPOSED METHOD

In this section, we propose a method to estimate the shape of a room based on a model fitting approach. Assume a room with 4 walls as the solid line in Fig. 1. First, direct echoes are extracted from $s(t)$ as in Fig. 3, the clue that direct echoes have relatively large negative values can be used. Next, the time delays d_i $(i = 0, 1, 2, 3)$ of these direct echoes are estimated; corresponding to the distance between the antenna and the i-th wall. Note that the i-th wall is expressed as:

$$x \cos\theta_i + y \sin\theta_i = cd_i/2, \qquad (2)$$

where c is the speed of light in a vacuum. Finally, unknowns $\Theta = (\theta_1, \theta_2, \theta_3, \theta_4)$ are estimated by solving:

$$\min_{\Theta} e(\Theta) = \sum_n |s(t_n) - s_0(t_n; \Theta)|^2, \qquad (3)$$

where $s_0(t_n; \Theta)$ is a computer-generated model signal assuming a multiple scattering environment with the parameter Θ.

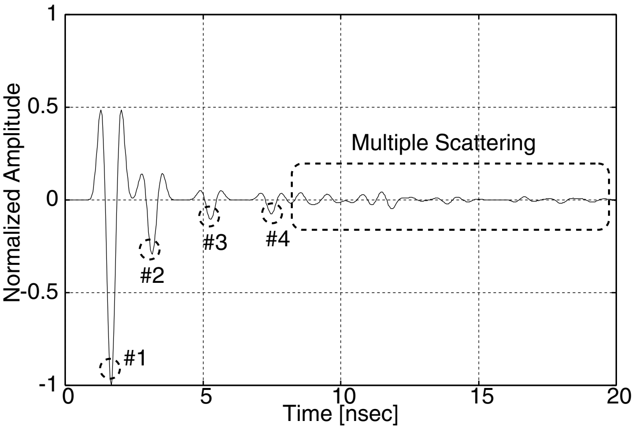

Fig. 3. Signal after applying the matched filter to the received signal.

A random search method is employed to optimize Eq. (3) as follows:

1) Initialize the parameters as $\theta_1 \leftarrow 0$, $\theta_2 \leftarrow \pi/2$, $\theta_3 \leftarrow \pi$, and $\theta_4 \leftarrow 3\pi/2$, and set $\Theta_{\text{best}} \leftarrow \Theta$.
2) Evaluate the value $e(\Theta)$ and set $e_{\text{best}} \leftarrow e(\Theta)$.
3) Randomly select θ_i, one of the parameters to be updated in the next step.
4) Update $\theta_i \leftarrow \theta_i + r$, where r is a random value satisfying $-r_{\text{m}} \leq r \leq r_{\text{m}}$. Here, $r_{\text{m}} = \pi\epsilon$, where ϵ is a positive value decreasing from 1 to 0 as the iteration proceeds.
5) Exchange θ_j and θ_k, two of the parameters as $\theta_j \leftarrow \theta_k$ and $\theta_k \leftarrow \theta_j$.
6) Evaluate the value $e(\Theta)$. If the value is smaller than e_{best}, update $e_{\text{best}} \leftarrow e(\Theta)$ and $\Theta_{\text{best}} \leftarrow \Theta$.
7) If e_{best} is smaller than a given threshold, exit. Otherwise, go to step 3.

V. NUMERICAL RESULTS OF ROOM SHAPE ESTIMATION

In this section, we show an example of the application of the proposed method. For the application, the signal $s(t)$ in Fig. 3 is used. Fig. 5 shows the residual value calculated in Eq. (3) at each iteration step. As in this figure, the residual value becomes less than 20% of the initial value after around 2,500 steps. The solid line in Fig. 6 shows the initial estimated room shape where only the distances d_i $(i = 0, 1, 2, 3)$ are accurately estimated while Θ is set to the initial value. The dashed lines in Fig. 4 show the numerically generated signals $s_0(t_n; \Theta)$ after 1, 1261 and 2477 iterations. This figure shows that $s_0(t_n; \Theta)$ gets close to the received signal $s(t)$ as the number of iterations increases. Figs. 7 and 8 show the estimated room shapes after 1261 and 2477 iterations, respectively. After 2477 iterations, the estimation is accurate enough to use for imaging employing TR methods.

VI. TIME-REVERSAL IMAGING USING ESTIMATED ROOM SHAPE

In this section, we show numerical results of time-reversal imaging using a room shape estimated in the previous section to check whether the proposed method is accurate enough

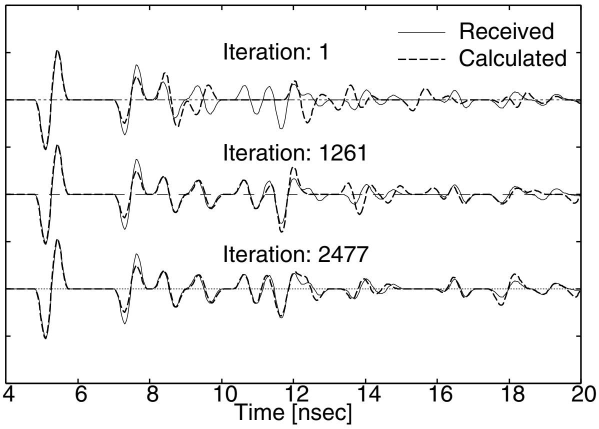

Fig. 4. Received and computer generated signals.

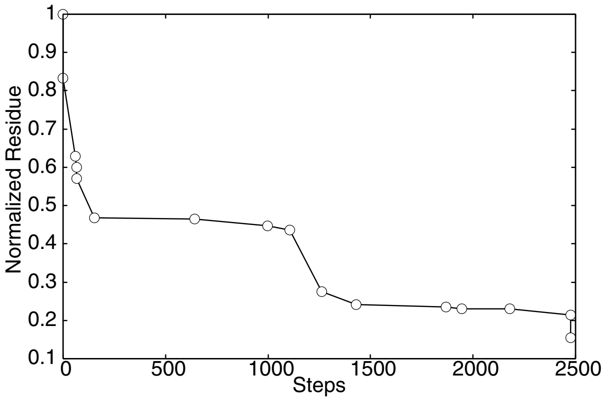

Fig. 5. Normalized residue value at each step.

to be applied to an actual target locationing processing. We assume a point-like target located at $(x, y) = (0.0\mathrm{m}, 1.0\mathrm{m})$ and calculate the scattered echoes in the same environment as in Fig. 1. The antenna is placed at the same position $(0.0\mathrm{m}, 0.0\mathrm{m})$ as in the previous section. The received signal $f(t)$ is shown in Fig. 9, where this signal is a residual component after subtracting the direct reflection from four walls as

$$f(t) = f_0(t) - s(t), \tag{4}$$

where $f_0(t)$ is the raw received signal, and $s(t)$ is the wall-reflection signals as in Fig. 3. The time-reversal imaging in Section III is then applied to obtain an estimation of target location.

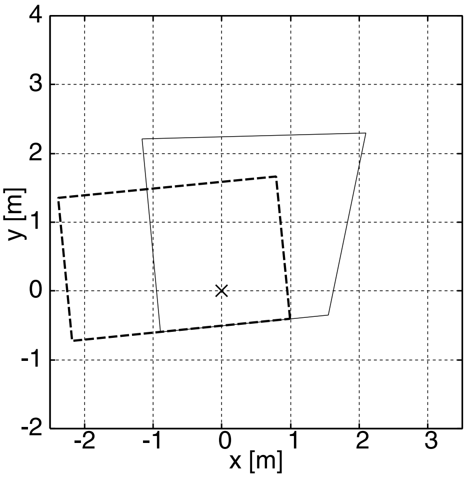

Fig. 6. Initial estimated room shape (dashed line).

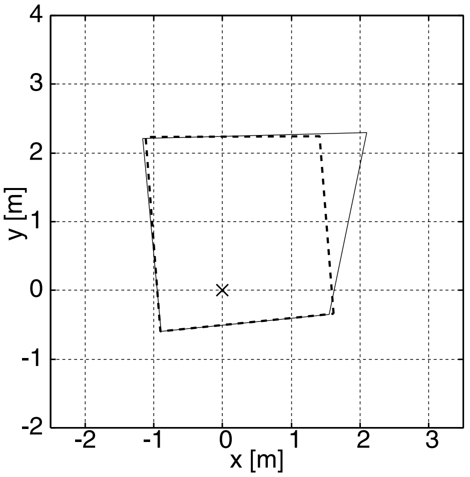

Fig. 7. Estimated room shape after 1261 iterations.

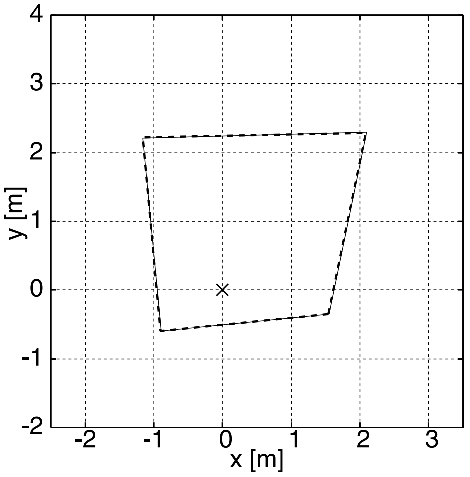

Fig. 8. Estimated room shape after 2477 iterations.

First, Fig. 10 shows the image by the time-reversal method assuming that the actual room shape is known. The image has a large value at the actual target location, meaning that the time-reversal imaging works properly where the multi-path environment is known.

Next, Figs. 11, 12 and 13 show the images estimated by the time-reversal method assuming the room shapes estimated in the previous section. Fig. 11 assumes the initial room shape in Fig. 6, where the estimated image does not give any meaningful estimation. This is because the initial room shape is far from the actual one where the time-reversal does not

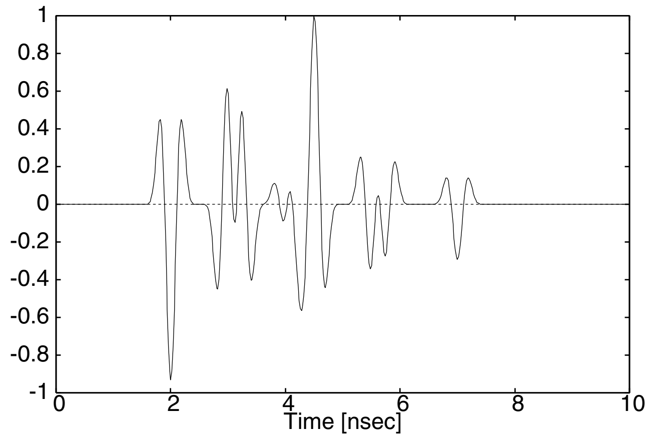

Fig. 9. Signal scattered from a point-like target in a multi-path environment.

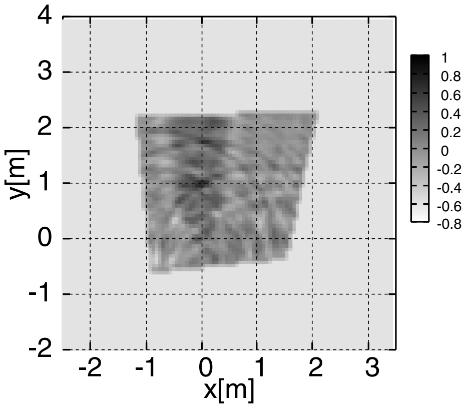

Fig. 10. Target image calculated with actual room shape (with a target located at (0.0, 1.0)).

work at all. Figs. 12 and 13 assume the room shapes estimated after 1261 and 2477 iterations, respectively. We see a large value around $(-0.3, 0.9)$ in Fig. 12 showing a better estimation than the initial one although the accuracy is not sufficient. The final estimation in Fig. 13 is much improved and close to the ideal estimation in Fig. 10. These results establish that the proposed room shape estimation method is accurate enough for the application of the time-reversal imaging.

VII. CONCLUSION

This paper proposed a model-fitting based method for the estimation of the shape of a room. The proposed method utilizes a single antenna system in a multipath environment. In a numerical simulation we showed that the proposed method accurately estimated a room shape, thus enabling high-resolution radar imaging with TR techniques such as DORT without any calibration procedure or reference targets to estimate the multipath environment. Some results of a TR imaging were shown, assuming the room shape estimated by the proposed method, confirming the effectiveness of the proposed method in an actual application to a target location estimation process.

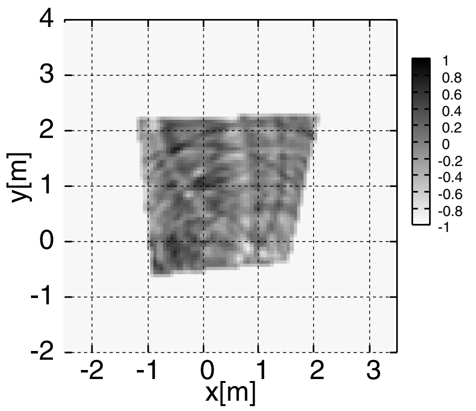

Fig. 11. Target image calculated with initial estimated room shape (with a target located at (0.0, 1.0)).

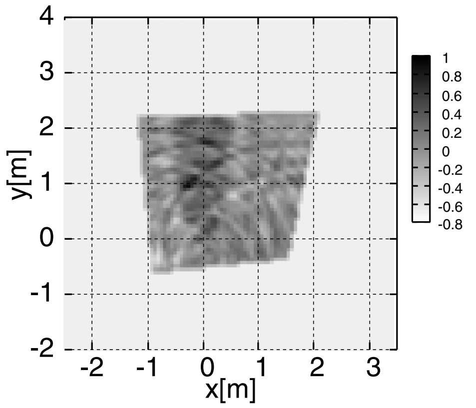

Fig. 12. Target image calculated with estimated room shape after 1261 iterations (with a target located at (0.0, 1.0)).

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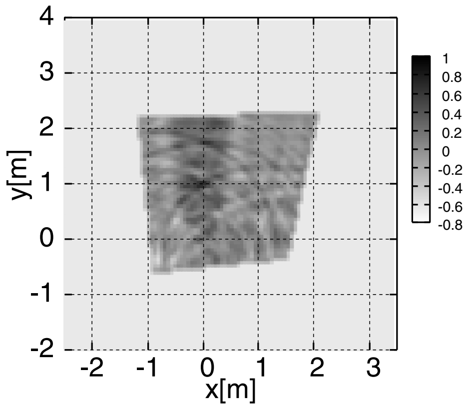

Fig. 13. Target image calculated with estimated room shape after 2477 iterations (with a target located at (0.0, 1.0)).

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