A TARGET TRACKING METHOD WITH A SINGLE ANTENNA USING TIME-REVERSAL UWB RADAR IMAGING IN A MULTI-PATH ENVIRONMENT

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ABSTRACT

UWB (Ultra Wide-Band) radar systems are promising imaging tools covering a variety of application fields including surveillance systems. UWB radar technology can provide advanced capabilities for current surveillance systems. An imaging algorithm for UWB radars, the TR (Time-Reversal) method enables high-resolution imaging in a multipath environment. Conventional TR methods have been applied to antenna array systems while our previous work proposed a TR method with a low-cost single antenna-based system. In this study, we propose a radar system with a single antenna on a vehicle in a multipath environment. This vehicle is assumed to get close to a moving target by adaptively tracking the target location. Some numerical simulation results show that the proposed low-cost system works well in a multi-path environment.

***Index Terms*—** UWB radar, surveillance system, multipath, time-reversal

1. INTRODUCTION

UWB radar systems are of great interest because they cover a variety of application fields including landmine detection, robotics, and security systems. In particular, surveillance systems have attracted much attention because they are indispensable in ensuring safety in our society. Although cameras are often used for surveillance systems due to their economical cost and high resolution, UWB radar technology can provide additional capabilities for current systems. UWB radars can obtain 3-dimensional images with relatively high resolution that are unachievable in conventional systems. The TR (Time-Reversal) method [1, 2] is an imaging algorithm for UWB radars, which provides a high-resolution capability in a multipath environment. Conventional TR methods have been applied to antenna array systems [3, 4, 5] but lead to a complex system that is too costly to use in practice. Our previous work [6, 7] proposed a TR method with a single antenna, which can be applied to a low-cost simple radar system. In practice, this approach removes the cost restriction when applying radar systems to common commercial products. In this study, we propose a radar system with a single antenna on a vehicle in a multipath environment. This vehicle is assumed to get close to a moving target by adaptively tracking the target location.

2. SYSTEM MODEL

Figs. 1 and 2 show the schematic of the proposed security system. The proposed system consists of a robot-like mobile machine with a UWB antenna, a transmitter, a receiver and a signal processing unit for imaging and control processes. This machine moves towards the position of a detected target to check it closely with, for example, an optical camera. Note that the radar system using the TR method and the multiple reflection waves can obtain an image in a blind-spot where targets are not directly visible to the radar system or cameras.

For simplicity, the electromagnetic wave propagation and room models are assumed to be 2-dimensional. The room is composed of two flat metallic walls as in Fig. 2. It is assumed that a mono-static radar system with a single omni-directional antenna is located at $\boldsymbol{x}_{\mathrm{a}}(T) = (x_{\mathrm{a}}(T), y_{\mathrm{a}}(T))$ and moves according to the imaging results. This antenna is used as a transmitter and receiver. A mono-cycle pulse with a center frequency of 1.0 GHz is transmitted from the antenna and the same antenna receives the echoes. 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 $s(t)$ at $T = 0$, in which we see multiple scattering echoes. This signal is generated numerically by employing a ray-tracing algorithm.

3. TIME-REVERSAL IMAGING AND TRACKING

The target location cannot be obtained by a single antenna in a free space because the radar system can estimate the distance to the target, but 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 using a low-cost practical sys-

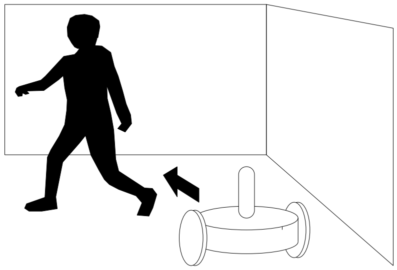

Fig. 1. Proposed security system.

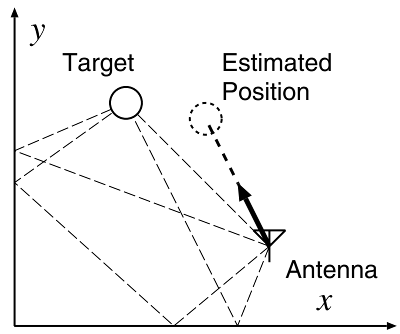

Fig. 2. A proposed security system and the system model.

tem 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. The TR image $I(x, y)$ is calculated as

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

where $\tau_i(x, y)$ is defined as the time delay between the antenna and the target via the i-th path. Fig. 4 shows each path between the antenna and the target. The target position is up-

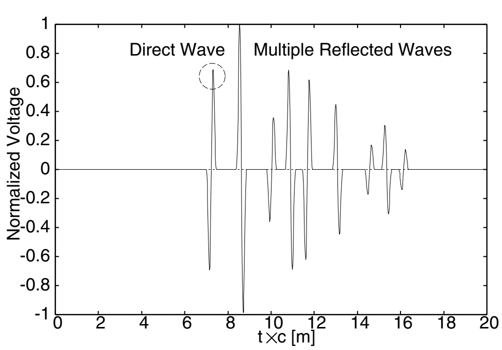

Fig. 3. An example of received signal at $T = 0$.

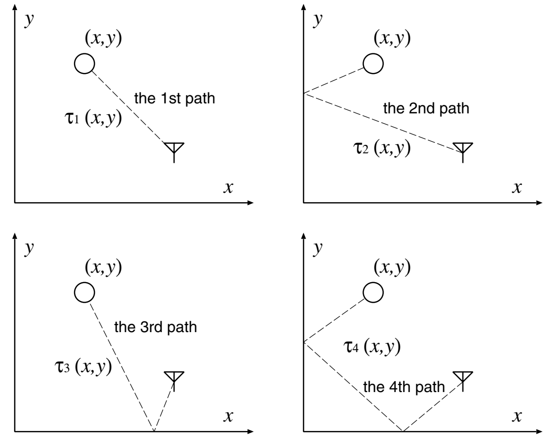

Fig. 4. Propagation paths between the antenna and the target via multiple reflections.

dated to get closer to the estimated target position as

$$\boldsymbol{x}_{\mathrm{a}}(T + \Delta T) = \boldsymbol{x}_{\mathrm{a}}(T) + \frac{\boldsymbol{x}_{\mathrm{target}}(T) - \boldsymbol{x}_{\mathrm{a}}(T)}{|\boldsymbol{x}_{\mathrm{target}}(T) - \boldsymbol{x}_{\mathrm{a}}(T)|} v\Delta T, \quad (2)$$

where v is the constant speed of the antenna on the vehicle. The tracking procedures are as follows:

1. Transmit a mono-cycle pulse and receive the scattered signal.
2. Subtract the reflections due to walls that are measured in advance from the scattered signal.
3. Apply the matched filter to the residual signal to produce $s(t)$.
4. Obtain the image by calculating Eq. (1) and extract the maximum valued pixel.
5. Move the system toward the estimated target position for a certain time ΔT as in Eq. (2).
6. Go back to the 1st step.

4. APPLICATION RESULTS

In this section, we assume the target is point-like and moving in a circle with the center at $(3.0\mathrm{m}, 3.0\mathrm{m})$ and a radius of 2 m at a speed of 1.6 m/sec. The security system with an antenna is assumed to be operated according to the procedure in the previous section, with a speed of 2.0 m/sec. Figs. 5 and 6 show the estimated images at two different antenna positions. In these figures, white circles show antenna positions, and black circles show target positions. In Fig. 5, multiple circles intersect and give the maximum value near the

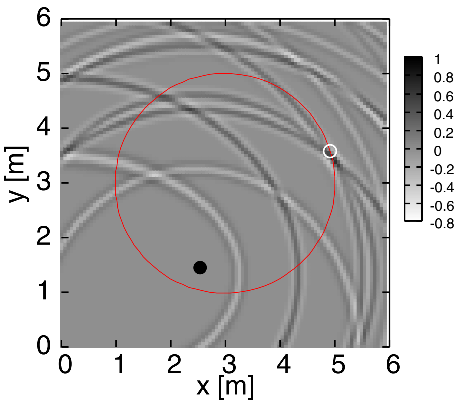

Fig. 5. Estimated image at non-symmetric antenna position.

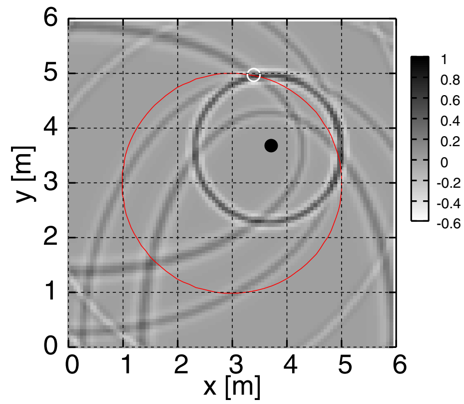

Fig. 6. Estimated image at symmetric antenna position.

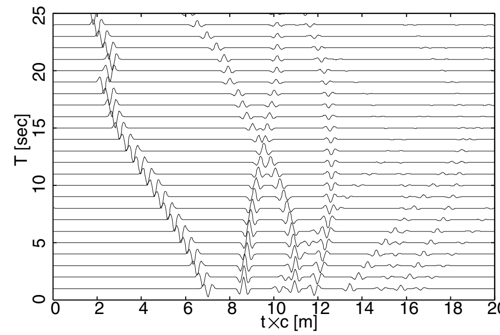

Fig. 7. Received signals.

true target position. Conversely, in Fig. 6, the image is completely symmetrical about the line $y = x$ because the antenna is located on this line and multiple reflection waves from the wall on x axis and the wall on y axis cannot be distinguished. Therefore, there is another peak at the symmetric position in addition to the true target position. This must be taken into account to determine the antenna motion, which is an important future task.

Figure 7 shows the received signals and the result of the tracking process, where black circles show the antenna position, and white circles show the target position. In Fig. 7 the leftmost echoes are direct waves without any reflections off the walls. As T increases, the delay time of the direct echo becomes smaller, meaning the antenna is getting closer to the target except for the irregular motion around $T \simeq 20$sec. Figure 8 shows the orbits of the target and antenna with white and black dots connected to each other. It is observed that the antenna is moving toward the target position, which means that target location based on TR imaging works effectively throughout the entire process. However, when the antenna is close to the symmetric line $y = x$, the antenna motion malfunctions for the above-mentioned reason.

5. ERROR ANALYSIS

As shown in the previous section, the error in estimating the target location occurs systematically due to the undesirable interference of multi-path echoes. To quantitatively evaluate the expected error determined by the antenna position, we calculate the RMS error for each antenna position $\boldsymbol{x}_a$ averaged in terms of the various target positions as

$$e\left(\boldsymbol{x}_{\mathrm{a}}\right) = \frac{1}{N}\sum_{n=1}^{N}\left|\boldsymbol{x}_{\mathrm{est}}\left(\boldsymbol{x}_{\mathrm{a}}\right) - \boldsymbol{x}_{\mathrm{target}}^{n}\right|^{2}, \tag{3}$$

where $N = 30 \times 30$ is the number of target positions equally located within $0\mathrm{m} < x_{\mathrm{target}} < 6\mathrm{m}$ and $0\mathrm{m} < y_{\mathrm{target}} < 6\mathrm{m}$, $\boldsymbol{x}_{\mathrm{target}}^{n}$ is the n-th target location assumed, and $\boldsymbol{x}_{\mathrm{est}}(\boldsymbol{x}_a)$ is the estimated target location using the TR method for the assumed antenna location $\boldsymbol{x}_a$. It is clearly observed that a large error is expected for the antenna on a diagonal straight line $y = x$ where multi-path propagation always has symmetry. Additionally, a large error is expected for the antenna in the area close to the walls in the corner. This is because multi-path echoes interfere with each other as the multiple paths have almost the same propagation delay time.

An important future task is to develop an elaborate algorithm to operate the antenna position so that it can avoid the areas where a large error is expected according to the RMS error map in Fig. 9.

6. CONCLUSIONS

In this paper, we proposed a security system with a robot-like machine with a UWB radar system. This radar system was assumed to be a simple low-cost one and to make use of multiple reflection waves to estimate target positions. We investigated the performance of the system with a numerical simulation and confirmed the basic characteristics of the system. The imaging became inaccurate when the antenna came close to

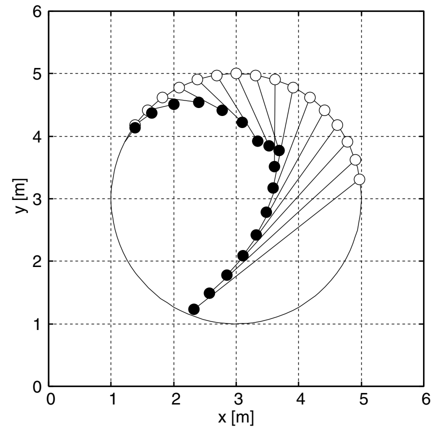

Fig. 8. The result of tracking process.

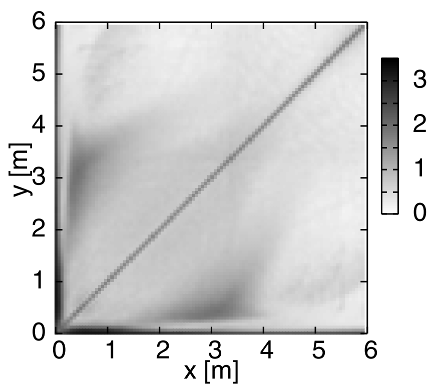

Fig. 9. Averaged RMS error for each antenna position.

a symmetric position, due to the ambiguity of the estimated image. A future task is to aim at improving the stability of the system by adaptively changing the processing depending on the multipath environment. The current detailed performance evaluation is in a realistic two wall environment while a multiple wall environment (more than 2) is an important issue to be tackled in the future.

7. REFERENCES

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