An Experimental Study on an Accurate UWB Radar Imaging Method for a Target with Unknown Motion using a Small Number of Antennas

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1. Introduction

Developing a cost-effective security system has been an important issue in crime prevention. Although cameras have been known as an effective candidate for this purpose, they have some limitations, such as difficulty in accurately estimating the three-dimensional shape of a target, and the exact distance to a target [1], [2]. Ultra-wideband (UWB) pulse radar is an alternative for resolving these problems of camera-based conventional systems. Although UWB radar imaging methods such as SAR (synthetic aperture radar) or other migration methods estimate target shape using simple and stable processes, the methods are not suitable for surveillance systems because the accuracy of the shape estimation is of a wavelength order, and estimation is time-consuming [3], [4]. SEABED (Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves) is known as a fast and highly accurate imaging algorithm for UWB pulse radars [5], [6]. SEABED assumes a system with a scanning antenna or array antennas and fixed targets. This costly type of system is, however, unrealistic for commercial applications such as surveillance systems. To overcome this problem, we proposed a new UWB radar imaging algorithm using the motion of targets instead of a scanning antenna [7-9]. This method has been improved to produce an accurate image of a target with arbitrary motion using three fixed antennas [10]. Numerical simulation showed that the proposed method is effective for accurately estimating a target shape with an RMS error less than 4 mm in a noisy environment with S/N=15 dB [11]. However, an experimental investigation on the proposed method has not yet been performed. This study applies the proposed UWB radar imaging method to experimental data measured in an anechoic chamber, and clarifies that the proposed method accurately estimates the shape of a target with an unknown motion even in an actual environment.

2. System Model

We assume a case where a human passes in front of antennas arranged along a wall. The system model in this paper is shown in Figure 1. For simplicity, we deal with two-dimensional problems in this paper. The x axis expresses a wall surface. The target is assumed to be a human body, and the objective is to estimate the shape of the target using antennas on the x axis. We use three antennas with a wide beam-pattern spaced at intervals of X_0. The positions of the antennas #1, #2, and #3 are defined as $(-X_0, 0)$, $(0, 0)$ and $(X_0, 0)$. We measure the distance from each antenna to a scattering object, and obtain $R_1(t)$, $R_2(t)$, and $R_3(t)$. Δt is defined as the IPP (Inter Pulse Period), and t_n as the n-th sampling time. Each measurement is independent of the positions of the other antennas in the system, which implies three mono-static radar systems. We assume that the radar signals do not interfere with each other, and the target motion $\boldsymbol{X}(t) = (X(t), Y(t))$ is an unknown function of time t. We assume a monocycle pulse with a centre frequency of 2.6 GHz as a transmit pulse waveform.

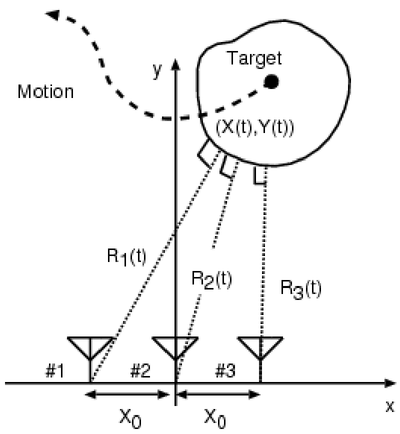

Figure 1: 2-dimensional system model.

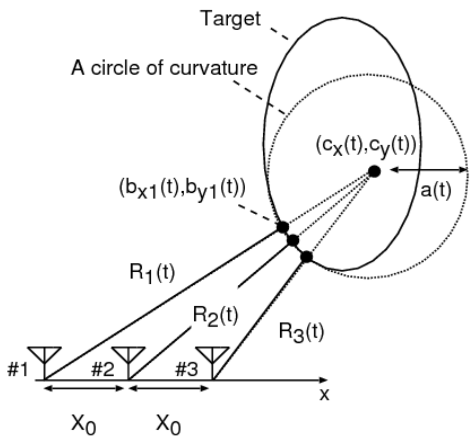

Figure 2:Estimating curvature using 3 antennas.

3. Proposed Method

The proposed method [10] estimates the target motion $\boldsymbol{X}(t) = (X(t), Y(t))$ and applies the SEABED algorithm using the estimated motion. First, the method approximates its target as part of a circle with a calculated curvature using each distance between the scattering object and an antenna, namely $R_1(t)$, $R_2(t)$, and $R_3(t)$. We define $\boldsymbol{c}(t) = (c_x(t), c_y(t))$ as the estimated center of curvature of the object at time t, $\boldsymbol{b}_i(t) = (b_{xi}(t), b_{yi}(t))$, ($i$ = 1, 2, 3) as the estimated scattered centers corresponding to antennas #1, #2, and #3, and $a(t)$ as the estimated radius of curvature as in Figure 2. Note that motion of the center of curvature $\boldsymbol{c}(t)$ is different from the actual motion of the target $\boldsymbol{X}(t)$. This is because $\boldsymbol{c}(t)$ includes the influence of the motion of the scattered centers $\boldsymbol{b}_i(t)$ that are not fixed.

To estimate the target motion accurately, it is necessary to modify the motion of the center of the scattering object correctly. The proposed method calculates an average curvature using the data obtained from two adjacent time steps. The average radius at each time step is calculated with $a(t_n)$ and $a(t_{n+1})$ as $\bar{a}(t_{n+1/2}) = (a(t_n) + a(t_{n+1}))/2$. Then, $\boldsymbol{c}(t_n)$ and $\boldsymbol{c}(t_{n+1})$ are recalculated based on the LMS criteria using this average radius to obtain updated $\bar{\boldsymbol{c}}(t_n)$ and $\bar{\boldsymbol{c}}(t_{n+1})$. An instantaneous velocity vector $\boldsymbol{v}_{n+\frac{1}{2}}$ is defined as:

$$\boldsymbol{v}_{n+\frac{1}{2}} = (\bar{\boldsymbol{c}}(t_{n+1}) - \bar{\boldsymbol{c}}(t_n)) / \Delta t\,. \tag{1}$$

Finally, the target motion is estimated as the sum of the estimated velocity vectors:

$$\bar{\boldsymbol{X}}(t_{N+\frac{1}{2}}) = \sum_{n=1}^{N} \boldsymbol{v}_{n+\frac{1}{2}} \Delta t. \tag{2}$$

Once the target motion is estimated, the SEABED algorithm can be applied to produce the target image. It has been shown that this method can estimate an accurate image even if the motion and the shape of the target are unknown.

4. Application of the Proposed Method to Experimental Data

In this section, we apply the proposed method to experimental data, and investigate the performance of the method in a practical situation. Figure 3 shows the experimental site for measuring echoes that is equivalent to the system assumed in the previous sections. This system is composed of two antennas, a robotic scanner and a metallic elliptic cylinder with cross section dimensions of 15 cm for the long axis and 10 cm for the short axis. We set the long axis of the cross section perpendicular to the ground. Two antennas for transmitting and receiving signals are set at 10 cm intervals parallel to the length of the cylinder. The antennas are mounted on a robotic scanner so that it can simulate data with an arbitrary target motion. Note that the antennas are scanned instead of the target because the signals in this measurement are determined only by the relative position of the target and antennas. The three white solid lines in Figure 3 show the orbits of the antennas #1, #2 and #3. To measure $R_1(t)$, $R_2(t)$, and $R_3(t)$ for 3 different antenna positions, we perform the measurement 3 times with different orbits corresponding to the relative positions of the antenna and the target, simulating the typical human motion caused by a periodic gait. The assumed motion is a zigzag human motion with an amplitude of 50 mm and velocity of 1.0 m/sec in the x direction while the IPP is set as $\Delta t = 5$ msec. One of the antennas transmits a UWB pulse with a centre frequency of 2.6 GHz and 3 dB-bandwidth of 800 MHz. We confirmed that the received signals have a S/N (Signal-to-Noise ratio) within $25\text{dB} \leq \text{S/N} \leq 41\text{dB}$ depending on the distance between the antennas and the target, and on the antenna pattern. Figure 4 shows the estimated distance between the antennas and the target using the matched filter applied to the received signals. The experimental data and the numerical simulation data are almost identical, with a maximum difference of 3 mm.

The solid line in Figure 5 shows the estimated target/antenna motion, which has a maximum error of 4 mm, meaning the proposed method can estimate the target motion even for actual measurement data. White circles in Figure 6 show the estimated target image points; the dotted line shows the actual section of the target shape. It is confirmed that the bottom part of the target shape is accurately estimated with the proposed method even though the target motion and shape are assumed to be unknown arbitrary functions. The RMS (Root-Mean-Square) error of the image estimation is 0.9 mm which corresponds to 0.01 wavelengths. The error is considered to be small enough for most security imaging systems.

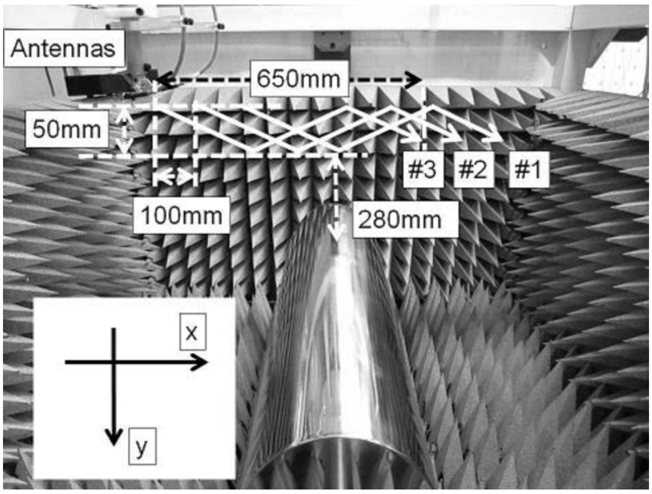

Figure 3: Experimental site for measuring a metallic elliptic cylinder.

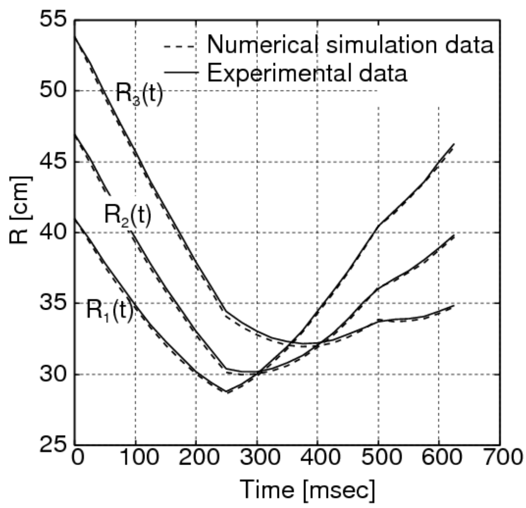

Figure 4: Measured range values $R_i(t)$ (i=1,2,3) vs. time.

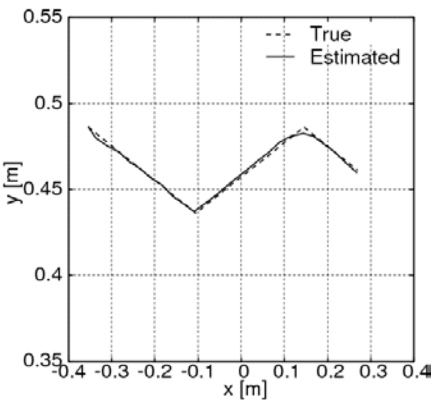

Figure 5: Actual and estimated target motion using the proposed method.

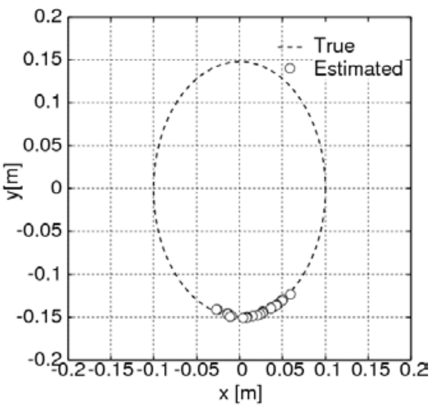

Figure 6: Target shape estimated using the proposed method.

5. Conclusions

We applied the proposed UWB radar imaging method to experimental data to clarify the effectiveness of the method. The proposed method uses 3 antennas to estimate the target motion and shape at the same time, by estimating the local curvature and the centre of the curvature circle of a target shape. The application example shows that the proposed method can estimate the target motion with an error of less than 4 mm, and the target image with an accuracy of 0.9 mm. These accuracies are high enough for most surveillance and security system requirements. It is an important future task to extend the proposed method to a 3-dimensional model to make it possible to apply in a more realistic experimental setup.

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