Study of a Method for 2-D Imaging of Simple-Shaped Targets with Arbitrary Motion using UWB Radar with a Small Number of Antennas

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Abstract

Ultra-wideband (UWB) pulse radar is an effective device as the basis for building a high-precision surveillance system. The fast SEABED (Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves) imaging algorithm is capable of accurately estimating target shapes using UWB pulse radar. A new UWB radar imaging algorithm, based on an extension of the SEABED algorithm that uses the motion of a target, was proposed in our previous work. This is unlike the conventional SEABED system that assumes a scanning antenna. Using a simple system with three fixed antennas, this imaging method has been verified as being viable even for targets with arbitrary motion. This study examines the performance limits of the method under various conditions. The numerical simulation establishes that the proposed method can accurately estimate the target shape even under severe conditions. Moreover, we clarify that the proposed method estimates a target shape with high accuracy and in a shorter time compared with conventional methods.

1. INTRODUCTION

In recent years, developing a reliable surveillance system has been a major issue in crime prevention. Although cameras have been universally prevalent as devices for security systems, they have some drawbacks, 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 efficient alternative for resolving these problems of camera-based conventional systems. Although UWB radar imaging methods such as synthetic aperture radar or migration methods estimate a target shape using simple and stable processes, the methods are not suitable for surveillance systems because the accuracy of shape estimation is of a wavelength order and is time consuming for estimating a target shape [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 radar [5], [6]. SEABED assumes a system with a scanning antenna or with 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]. However, the qualitative performance limits and necessary conditions for the method have not yet been studied.

This study numerically investigates the effects of a variety of conditions on the image estimated by the proposed method. The conditions include motion, target shape and antenna distance. Moreover, we establish that the proposed method is effective for accurately estimating target shape compared with a conventional method.

2. SYSTEM MODEL

The system model in this paper is shown in Fig. 1. For simplicity, we deal with two-dimensional problems in this paper. The target is assumed to be a human body, and the objective is to estimate the shape of the target. We use three omni-directional antennas 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 monostatic 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

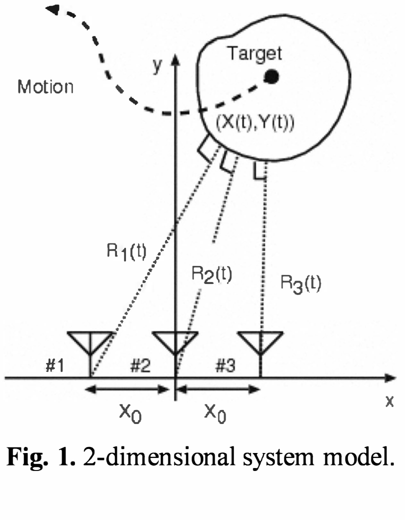

Fig. 1. 2-dimensional system model.

t. We assume a monocycle pulse with a center frequency of 6.0 GHz as a transmit pulse waveform.

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 Fig. 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

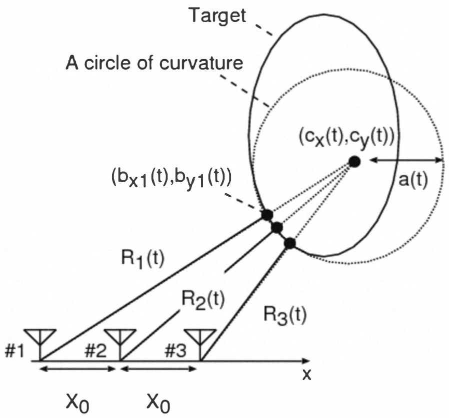

Fig. 2. Parameters of a circle of curvature.

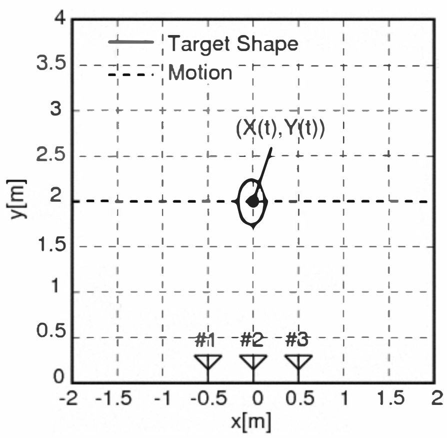

Fig. 3. System model for the numerical simulation.

$a(t_{n+1})$ as $\bar{a}(t_{n+\frac{1}{2}}) = (a(t_n) + a(t_{n+1}))/2$. 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.

4. PERFORMANCE EVALUATION OF THE PROPOSED METHOD

In this section, we apply the proposed method to a moving target under various conditions, and investigate the performance limits of the method using numerical simulation. The calculation parameters for the simulations are as follows: a target shape is assumed to be a slant ellipse with a long axis of B and a short axis of W, and the distance between antennas is X_0.

4.1. Examination of the proposed method when applied to various target motions

First, we assume a target motion under acceleration in the X-Y plane $(X(t), Y(t))$ along a straight line at $Y(t) = 2.0$ m and $X(t)$ as in Fig. 4. The target speed changes within a realistic range from 0 m/sec to 4 m/sec in 4 sec. Δt is assumed to be 4 msec in this study. We assume that $X_0 = 0.5$ m, $B = 0.25$ m, $W = 0.15$ m as in Fig. 3. This represents the approximate size of a section of a human body. For simplicity, we assume ideal conditions without noise.

Fig. 4. shows the target motion estimated by the proposed algorithm. The actual and estimated curves overlap almost entirely, meaning that the motion estimation process works well for this example. Fig. 5.

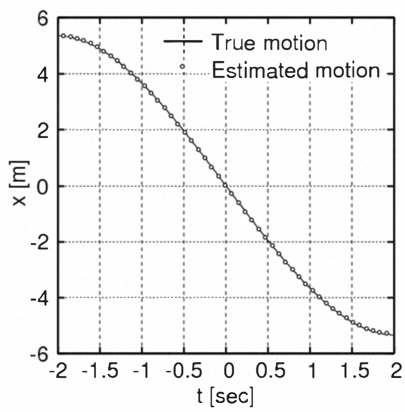

Fig. 4. Actual target motion and estimation using the proposed method.

shows the actual and estimated target shapes. The RMS (Root Mean Square) error of the estimated shape is approximately 0.63 mm, which corresponds to 0.25 % and 0.42 % of the long and short axes of the target shape. Thus, it is established that the proposed method can accurately estimate the motion and shape of a target even if the motion involves a large acceleration.

4.2. Examination of the proposed method when applied to various target shapes

Next, we investigate the estimation accuracy of the proposed method for different target shapes. We change the target shape by changing the ratio W/B between the long axis B and short axis W of an el-

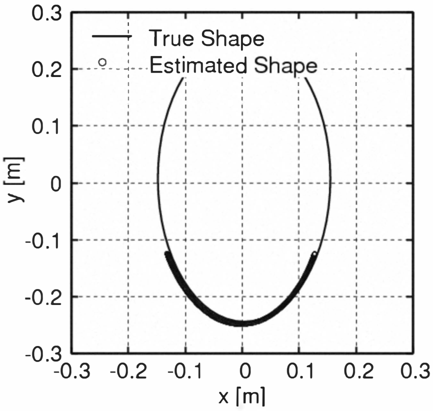

Fig. 5. Target shape estimated using the proposed method for an accelerated target motion.

lipse. Here, the cross-sectional area of the target is fixed at 0.04 m^2. The target motion is $(X(t), Y(t)) = (v_x.t, y_0)$, where $v_x = -1.0$ m/sec, $y_0 =$ 2.0 m, and $X_0 =$ 0.5 m.

We see that the RMS error becomes relatively large for large W/B in Fig. 6. This is because the three scattering centers move apart from each other. The separated scattering centers reduce the accuracy

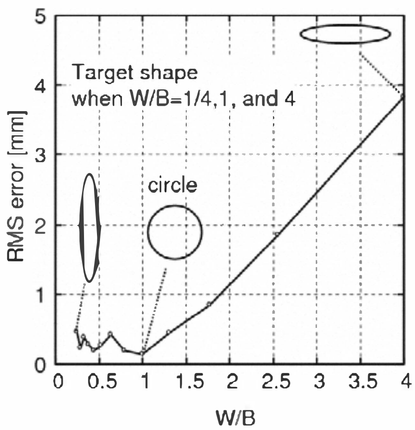

Fig. 6. RMS error versus the ratio of the long and short axis of the target.

of estimating curvatures in the proposed method, because we estimate the curvature circle by estimating a circle on which three scattering centers are located.

The RMS error is the smallest for $B = W$ as in Fig. 6. This is because the target shape is a complete circle in this situation, and the approximation process using a circle of curvature is not an approximation but a direct expression of the target shape in this case. If the target shape is an ellipse, this approximation has a certain error, requiring the averaging of two adjacent curvatures. In contrast, the curvature averaging process is not needed at all if the target shape is a circle.

4.3. Examination of the influence of an antenna interval

Finally, we investigate the performance of the proposed method with different antenna intervals. The target motion is given as $(X(t), Y(t)) = (v_x.t, y_0)$, where $v_x = -1.0$ m/sec, $y_0 = 2.0$ m. We assume $B = 0.25$ m and $W = 0.15$ m. We add Gaussian noise to $R_1(t)$, $R_2(t)$, and $R_3(t)$ with a S/N ratio of 15 dB, which is an approximation of added white Gaussian noise being included in the received signals. A relationship between the signal-to-noise ratio (S/N) and the standard deviation of the Gaussian random error in $R_1(t)$, $R_2(t)$, and $R_3(t)$ is shown in [5]. Next, we smooth them with a Gaussian function with correlation length of 1 cm.

The RMS error becomes very large when the antenna interval is smaller than 0.2 m, as in Fig. 7. This is because the parameters of the calculated circle of curvature have unstable values. When the antenna interval is short, $R_1(t)$, $R_2(t)$, and $R_3(t)$ are almost the same. Therefore, the parameters of the circle of curvature are changed sharply by slight noises. For this reason, motion and shape estimation by the proposed method has a large error in this case.

We see that the RMS error becomes relatively large for large X_0 as shown in Fig. 7. This is because the circle of curvature is not in agreement with a section of the target. When the antenna interval is short, since the scattered centers on the target are close together, the accuracy of the approximation to the circle is good. However, when the antenna interval is long, the accuracy of the approximation deteriorates.

5. PERFORMANCE COMPARISON WITH A CONVENTIONAL METHOD

In this section, we compare the imaging accuracies of the proposed method and a conventional method. The reverse-time migration method [4] is used as the conventional method for this comparison. The conventional method obtains an image by linearly superposing received signals compensating for the delay and power, assuming the actual target motion is known. We assume the target motion is $(X(t), Y(t)) = (v_x.t, y_0)$, where $v_x = -1.0$ m/sec, $y_0 = 2.0$ m. Target shape is assumed to be an ellipse with a long axis of 0.25 m and a short axis of 0.15 m, and the antenna interval is 0.5 m. Fig. 8. shows the target shape estimated using the conventional method.

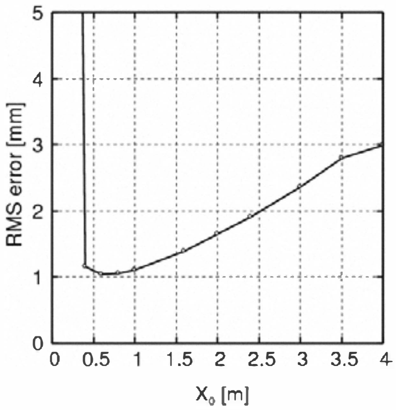

Fig. 7. RMS error versus the antenna distance X_0

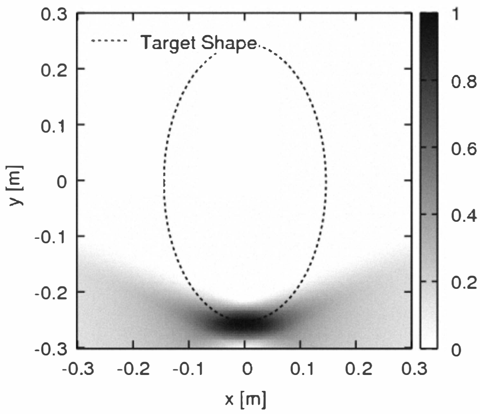

Fig. 8. Target shape estimated using a conventional method.

The resolution of the image is not high enough to estimate the target shape, while the proposed method can estimate a clear target shape as in Fig. 5.

Note that the conventional method is even more time-consuming than the proposed one; the conventional and proposed methods take 74 sec and 0.01 sec to calculate the image, using a 2.2 GHz Intel Pentium Dual CPU E2200 processor.

6. CONCLUSIONS

In this paper, we verified that the proposed method realizes accurate imaging under various conditions, and established the application limits of the method using the RMS error of the differences between the actual and estimated shapes. Even if the target motion contains acceleration, it has been verified that the proposed method can estimate the target motion and shape with high accuracy, and that the RMS error is 0.63 mm in this study. Moreover, the proposed method can accurately estimate a target shape with a relatively large curvature, or a target shape close to a circle. The RMS error is 0.46 mm and 3.8 mm for $W/B = 1/4$ and 4, and reaches a minimum of 0.14 mm for $B = W$. When the antenna interval is smaller than 0.2 m, the proposed method does not work well because of the influence of noise. The RMS error drops to 1.0 mm for an antenna interval of 0.6 m. Finally, we verified that the proposed method estimated a target shape with high accuracy and in a shorter time compared with a conventional method.

7. REFERENCES

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