Real-time Imaging of Human Bodies with UWB Radars using Walking Motion

Takuya SAKAMOTO and Toru SATO
Department of Communications and Computer Engineering, Kyoto University
Kyoto, 606-8501, Japan

Abstract— **UWB(Ultra Wide-Band) pulse radar is a promising candidate for surveillance systems used to prevent crimes and terror. The high-speed "SEABED" (Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves) imaging algorithm is deployed to apply UWB pulse radar in fields that require realtime operations. The SEABED algorithm is based on a reversible BST (Boundary Scattering Transform) between the target shape and the received data. This transform does not require the iterative calculations needed by other algorithms such as the synthetic aperture method or the domain integral equation method. The SEABED algorithm assumes that omni-directional antennas are scanned to observe the scattered electric field in each location. However, in the field of surveillance systems, scanning antennas are impractical. In this paper, walking motion is used to replace scanning antennas. We propose a new algorithm to estimate the shape of a human body using the data provided by a human body passing stationary antennas.**

Keywords—**UWB radar, SEABED algorithm, walking motion, surveillance system**

I. Introduction

UWB(Ultra Wide-Band) pulse radar is a promising candidate for surveillance systems used to prevent crimes and terror. UWB pulse radar can be installed in private areas where cameras cannot be used because of the resulting effect on privacy. It is possible to obtain the shapes of bodies without their surface textures using the UWB pulse radar. A variety of algorithms have been proposed to estimate target shape with observed radar data [1], [2], [3]. However, most of these are based on iterative procedures, which makes the calculation time too long for the applications required by surveillance systems. We have developed "SEABED", a high-speed imaging algorithm [4], [5], [6], to enable the use of UWB pulse radar to fields that require realtime operations, such as those in automobiles and robotics, and surveillance. Surveillance systems need to finish processing signals to obtain the image within a short time to prove useful. The SEABED algorithm is indispensable in this task. The SEABED algorithm is based on a reversible BST (Boundary Scattering Transform) between the target shape and the received data and does not require iterative calculations. Other algorithms used in this kind of application use iterative calculations such as the synthetic aperture method or the domain integral equation method [7].

The SEABED algorithm assumes that omni-directional antennas are scanned to observe the scattered electric field in each location. In the field of robotics, robot motion can be easily made to match the scanning process. However, for surveillance systems the motion of radar devices is limited because they are usually installed on walls or other fixed observation points. For this reason scanning antennas are not realistic for surveillance systems. In this paper, walking motion is used to replace the need for scanning antennas. Data is instead gathered from signals from various antennas with differing relative positions to the subject. This data is approximately equal to the data obtained by scanning antennas except in one key facet; the instantaneous velocity of any given walking motion is an unknown variable which changes as a function of time. We propose a new algorithm that solves this problem and uses the available data to estimate the shape of a human body.

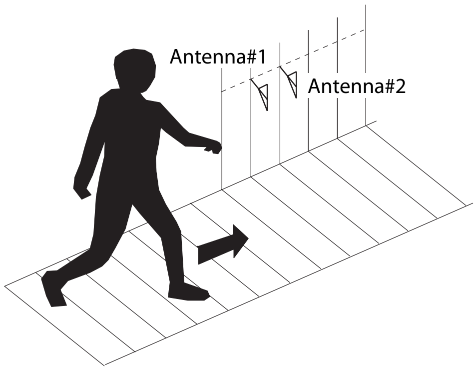

Fig. 1. Antenna arrangement for imaging human bodies.

II. System Model

For the purposes of this paper it is assumed that the radar is installed on the walls in passageway as in Fig. 1. People tend to walk approximately uniformly in passageways in subways and airports, compared to other places such as outside in the open. The motion is not completely uniform; this non-uniformity can be seen as an unknown function.

For simplicity, we deal with a 2-dimensional problem in this paper, where the objective is to estimate the shape of the cross section of the human body. We use a pair of omni-directional antennas with a certain distance X_0. We measure the range between the scattering center and each antenna. We assume a dual monostatic radar system instead of a bistatic radar system. In this paper, we assume the direction of the walking motion is parallel to the baseline of the antennas and the speed is an unknown function of time. Fig. 2 shows the 2-dimensional system model dealt with in this paper.

Only the position of the antennas relative to the target

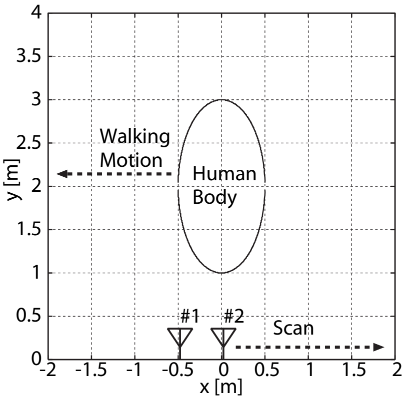

Fig. 2. 2-dimensional system model.

object is considered, inverting the problem to be solved, to be one estimating the unknown motion of the antennas relative to a 'stationary' target object. The problem is viewed in this way in the following discussions purely for simplicity.

III. The SEABED Algorithm

A fast BST (Boundary Scattering Transform) based radar imaging algorithm was developed [4], [7]. The algorithm is named SEABED: Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves. The algorithm uses the existence of a reversible BST between target shapes and pulse delays. SEABED has the advantage of direct estimation of target boundaries using the inverse transform, a mathematically complete solution for the inverse problem as been shown [4]. It is assumed that each target has a uniform complex permittivity, and is surrounded by a clear boundary. It is also assumed that the propagation speed is known. Here, we assume the medium of the direct path is a vacuum for simplicity.

The upper part of Fig. 3 shows an example of a target shape. A strong scatter is received from the point P in the figure. The distance Y between the point P and the antenna $(X, 0)$ is easily obtained from UWB radar. The relationship between X and Y is shown in the lower part of Fig. 3. We call this curve a 'quasi wavefront'. The BST is expressed as

$$X = x + y\frac{\mathrm{d}y}{\mathrm{d}x}, \tag{1}$$

$$Y = y\sqrt{1+\left(\frac{\mathrm{d}y}{\mathrm{d}x}\right)^2}, \tag{2}$$

where (X, Y) is a point on a quasi wavefront, and (x, y) is a point on the target boundary [4]. As stated above the inverse transform of the BST is given by

$$x = X - Y\frac{\mathrm{d}Y}{\mathrm{d}X}, \tag{3}$$

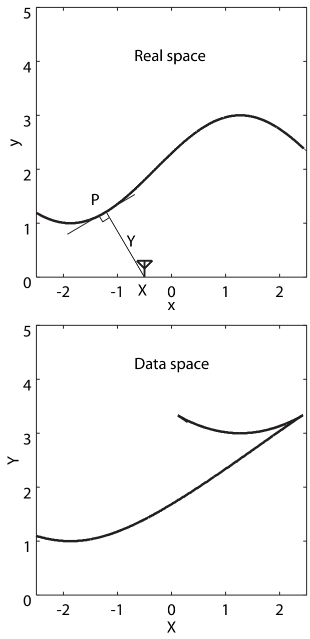

Fig. 3. An example of a target shape and a quasi wavefront.

$$y = Y\sqrt{1-\left(\frac{\mathrm{d}Y}{\mathrm{d}X}\right)^2}, \tag{4}$$

where we assume $|\mathrm{d}Y/\mathrm{d}X| \leq 1$. This condition is required because y should be a real number and can be used as a clue to estimate quasi wavefronts from the received signals. We call the transform in Eqs. (3) and (4) Inverse Boundary Scattering Transform (IBST).

First, quasi wavefronts are extracted from the received signals $s(X, Y)$ in the SEABED algorithm. Quasi wavefronts are extracted to satisfy the conditions $\mathrm{d}s(X, Y)/\mathrm{d}Y = 0$ and $|\mathrm{d}Y/\mathrm{d}X| \leq 1$. Next, quasi wavefronts with a large evaluation value, calculated by summing the signal power along the estimated quasi wavefront, are selected. Finally, the IBST is applied to the quasi wavefronts to obtain the final image.

IV. Observed Data with Unknown Scanning Speed

In the SEABED algorithm, the IBST is applied to the quasi-wavefront $Y(X)$ to obtain the estimated shape (x, y). The quasi-wavefront is the relationship between the antenna position X and the delay time Y. It should be noted that the antenna position is not known; the position X must, therefore, be estimated to obtain the quasi-wavefront.

The positions of the antennas 1 and 2 at time t are $(X(t), 0)$ and $(X(t) + X_0, 0)$, respectively because the distance between the antennas is X_0, which is also normalized by the center wavelength. Under this assumption, the delay time observed with the pair of antennas is

$$Y_1(t) = Y(X(t)), \tag{5}$$

and

$$Y_2(t) = Y(X(t) + X_0) \tag{6}$$

as a function of time t with the quasi-wavefront $Y(X)$. It is important to note that these functions are composite functions of $X(t)$ and $Y(X)$. These equations of $Y_1(t)$ and $Y_2(t)$ are required to estimate the original functions $X(t)$ and $Y(X)$. If $Y(X)$ is correctly estimated, it is easy to estimate the target shape using the IBST as described in the previous section.

V. Proposed Algorithm

We propose an algorithm to estimate $X(t)$, which readily leads to the estimation of $Y(X)$. First, the pair of times t_1 and t_2 which satisfies $Y_1(t_1) = Y_2(t_2)$ is calculated. It then follows that the antennas are located at the same position at t_1 and t_2, respectively. The t_1 and t_2 pair is sequentially calculated, and estimate the continuous function $\tau(t)$, that satisfies

$$Y(X(\tau(t))) = Y(X(t) + X_0). \tag{7}$$

This, in turn, is equal to the condition $t_1 = \tau(t_2)$. In order to obtain the function $\tau(t)$, we roughly match the delay times $Y_1(t)$ and $Y_2(t)$ with the average time difference t_0. Here, t_0 is a constant and approximately satisfies

$$Y_1(t + t_0) \simeq Y_2(t), \tag{8}$$

which is determined using the peak time of the cross-correlation function of $Y_1(t)$ and $Y_2(t)$ as

$$t_0 = \mathrm{argmax}_{t_0} \left| \int Y_1(t + t_0) Y_2(t) \mathrm{d}t \right|^2. \tag{9}$$

Next, the minute adjustment function $\Delta\tau(t)$ must be solved to satisfy

$$Y_1(t + t_0 + \Delta\tau(t)) = Y_2(t), \tag{10}$$

where $\Delta\tau(t)$ is estimated by a simple linear search. If multiple candidates that satisfy the condition in Eq. (10) are found for $\Delta\tau(t)$, the nearest can be adopted. Then, the function $\tau(t) = t + t_0 + \Delta\tau(t)$ is obtained.

The function $\tau(t)$ approximately satisfies $X(\tau(t)) = X(t) + X_0$. The equation

$$\frac{X(\tau(t)) - X(t)}{\tau(t) - t} = \frac{X_0}{\tau(t) - t} \tag{11}$$

can then be easily derived. If the time difference $|\tau(t) - t|$ is small, the left-hand side of Eq. (11) can be approximated as the derivative $\mathrm{d}X/\mathrm{d}t$. However, if $|\tau(t) - t|$ is not small enough, the approximation has a time offset.

Interestingly, we can also derive another equation as

$$\frac{X(t) - X(\tau^{-1}(t))}{t - \tau^{-1}(t)} = \frac{X_0}{t - \tau^{-1}(t)}. \tag{12}$$

Here, the inverse function $\tau^{-1}(t)$ naturally satisfies $t_2 = \tau^{-1}(t_1)$ similarly to $t_1 = \tau(t_2)$. The left-hand side of the equation is approximated as the derivative $\mathrm{d}X/\mathrm{d}t$. Eq. (12) also has an offset. The following approximation can be adopted as a compromise

$$\frac{\mathrm{d}X}{\mathrm{d}t} \simeq \frac{X(\tau(t)) - X(\tau^{-1}(t))}{\tau(t) - \tau^{-1}(t)} = \frac{2X_0}{\tau(t) - \tau^{-1}(t)}. \tag{13}$$

The right-hand side of Eq. (13) is calculated with the estimated $\tau(t)$. Then, an integration is performed to estimate $X(t)$ as

$$X(t) \simeq \int \frac{2X_0}{\tau(t) - \tau^{-1}(t)} \mathrm{d}t + C, \tag{14}$$

where C is an integral constant. This constant C cannot be determined with observed signals. However, we do not care about the constant C because it influences the position, not the shape.

Finally, the quasi-wavefront $Y(X)$ is calculated using the estimated $X(t)$ with Eq. (5). The target shape can be obtained by applying IBST to the estimated quasi-wavefront.

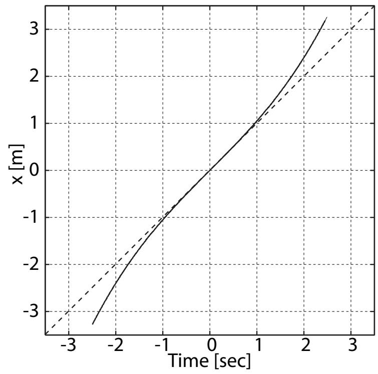

Fig. 4. Assumed relative position and uniform motion in the conventional SEABED algorithm.

VI. Application of the Proposed Algorithm

This section discusses examples of the practical application of the proposed algorithm. It is assumed that the true target shape is an ellipse as shown in Fig. 2. The distance between the antennas is set to 0.5λ, where λ is the center wavelength. The speed of the walking motion is assumed to change according to the solid line in Fig. 4 with an average speed of 1m/s, as shown as the dashed line in this figure.

Fig. 5 shows the estimated range data for the antennas. If the walking motion is uniform with a known velocity, it is possible to estimate the target shape by applying IBST. First, the IBST is applied to the data in Fig. 5 assuming the uniform motion with the speed of 1m/s to obtain the target shape in Fig. 6. The estimated shape has a large error except around $x = 0$. Here this is because the assumed speed is equal to the average motion at $t = 0$ and $x = 0$ as in Fig. 4. The conventional SEABED algorithm assumes antenna scanning motion is uniform, which causes this kind of large error in the estimated image.

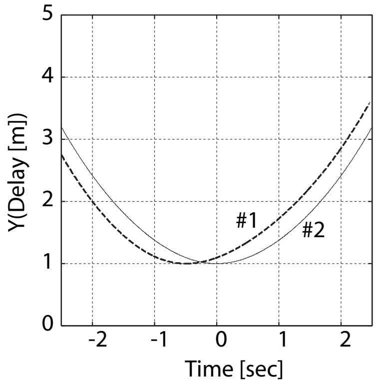

Fig. 5. Observed range vs. time.

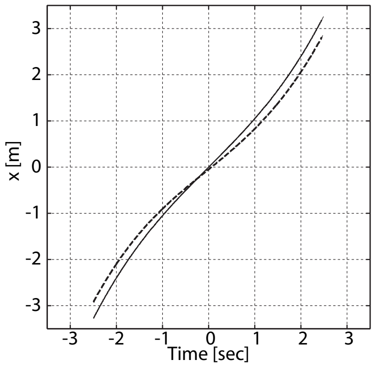

Fig. 7. Estimated relative position by interferometric measurement for a point target.

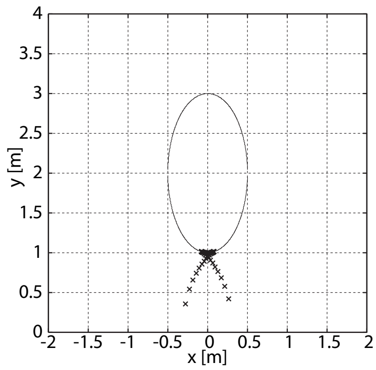

Fig. 6. Estimated target shape using the conventional SEABED algorithm.

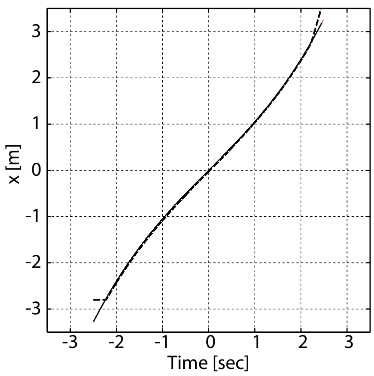

Fig. 8. Estimated relative position using the proposed algorithm.

Interferometry techniques are often used to estimate target motion in this field. This technique, however, assumes that the scattering center is fixed. If this assumption is satisfied, the motion $X(t)$ can be estimated as $X(t) = (Y_1(t)^2 - Y_2(t)^2 + X_0^2)/2X_0$, which is calculated as the dashed line in Fig. 7; the true motion shown as the solid line. Here the estimated motion is close to the true motion when compared to the approximation using uniform motion. However, the estimation error is still not negligible, because the assumption that the scattering center is fixed is unrealistic, and results in moving the scattering center relative to the scanning antenna.

Fig. 8 shows the estimated motion produced by the proposed algorithm. The estimation error is smaller than that of conventional interferometry. Fig. 9 shows the estimated target shape with the proposed algorithm. The shape is accurately estimated, as the error estimating the walking motion $X(t)$ is small enough for the imaging process using the proposed algorithm.

VII. Conclusion

This paper discusses the application of a UWB radar imaging system as a surveillance system. We used walking motion to replace antenna scanning to observe the electric field in various positions, where walking motion is an unknown function of time. A new algorithm to estimate both walking motion and target shape was proposed. We approximated the derivative of the walking motion as a function calculated on observed data, and used this to show several examples of application of the algorithm and that it works well even for unknown walking motion. Analyzing the performance of the proposed algorithm for arbitrary walking motion will yield important information and should be pursued.

References

[1] E. J. Bond, X. Li, S. C. Hagness, and B. D. van Veen, "Microwave imaging via space-time beamforming for early detection of breast cancer," IEEE Trans. Antennas Propagat., vol. 51, no. 8, pp. 1690–1705, 2003.

[2] J. van der Kruk, C. P. A. Wapenaar, J. T. Fokkema, and P. M. van den Berg, "Three-dimensional imaging of multicomponent ground-penetrating radar data," Geophysics, vol. 68, no. 4, pp. 1241–1254, 2003.

[3] T. Sato, T. Wakayama, and K. Takemura, "An imaging algorithm of objects embedded in a lossy dispersive medium for subsurface radar data processing," IEEE Trans. Geosci. Remote Sensing, vol. 38, no. 1, pp. 296–303, 2000.

[4] T. Sakamoto and T. Sato, "A target shape estimation algorithm for pulse radar systems based on boundary scattering transform," IEICE Trans. Commun., Vol. E87-B, No. 5, pp. 1357–1365, May, 2004.

[5] T. Sakamoto and T. Sato, "A phase compensation algorithm for

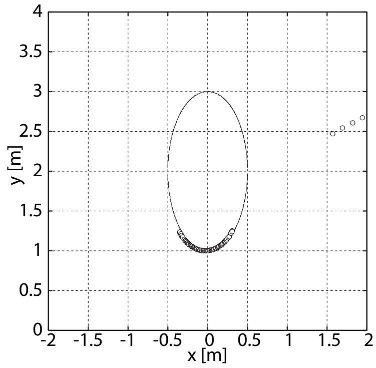

Fig. 9. Estimated target shape using the proposed algorithm.

high-resolution pulse radar systems," IEICE Trans. Communications, vol. E87–B, no. 11, pp. 3314–3321, Nov., 2004.

[6] T. Sakamoto, "A 2-D image stabilization algorithm for UWB pulse radars with fractional boundary scattering transform," IEICE Trans. on Commun. vol.E90-B, no.1, pp.131-139, Jan., 2007.

[7] T. Sakamoto, "A fast algorithm for 3-dimensional imaging with UWB pulse radar systems," IEICE Trans. on Commun., vol.E90-B, no.3, Mar, 2007.(in press)