A Study on Fast Imaging for Walking Human Bodies by UWB Radar with Realistic Model

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***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 assumes that omni-directional antennas are scanned to observe the scattered electric field in each location. However, for surveillance systems, antenna scanning is impractical. The instantaneous velocity of any given walking motion is an unknown variable which changes as a function of time. In our previous work, walking motion was used to replace antenna scanning by assuming a simple model of walking motion. In this paper, we measure a real walking motion and determine a realistic walking model. We investigate the performance of the proposed algorithm with this realistic model.**

I. Introduction

Radar imager is a promising candidate for surveillance systems used, amongst other things, to prevent crimes and terror. Radar can be installed in private areas where cameras cannot be used because of the resulting effect on privacy. Lin and Ling [1], [2] proposed a low-complexity CW (Continuous Wave) radar system for frontal imaging of moving human. They experimentally confirmed that the moving body parts were derived to construct a frontal view of a human. Their technique, however, is based on the assumption that different body parts give rise to different Doppler frequencies. It is difficult to meet this condition in practice, which leads to inaccurate human image.

UWB (Ultra Wide-Band) pulse radar is an alternative candidate. It is reliable as a surveillance system because it does not depend on Doppler frequencies. We have developed SEABED, a high-speed imaging algorithm [3], [4], [5], to enable the use of UWB pulse radar in areas that require realtime operations, such as surveillance. 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.

The SEABED algorithm assumes that omni-directional antennas are scanned to observe the scattered electric field at each location. For surveillance systems the motion of detection devices is limited because they are usually installed on walls or other fixed observation points. For this reason antenna scanning is not realistic for surveillance systems. In our previous work, walking motion was used to replace the need for scanning antennas [7]. 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 of 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 proposed an algorithm that solves this problem to estimate the shape of a human body. In this paper, we measure a real walking motion and determine a realistic walking model. We investigate the performance of the proposed algorithm with this realistic model.

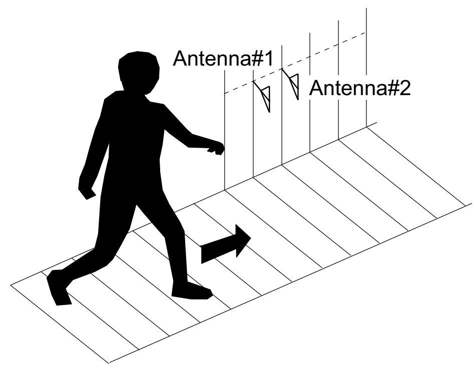

Fig. 1. Antenna arrangement for imaging human bodies.

II. System Model

For the purposes of this paper it is assumed that the radar is installed on walls in passageways as in Fig. 1. The walking 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 at a certain distance; X_0. We measure the range between the scattering center and each receiving antenna. The measurement is independent of the position of the other antenna in the system, which means that we assume a dual monostatic radar system instead of a bistatic radar system.

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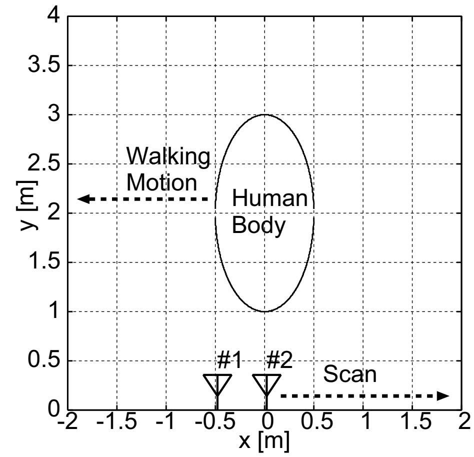

Fig. 2. 2-dimensional system model.

This dual monostatic radar system is realized by introducing a spectrum spreading modulation with two different codes assigned to the antennas [8]. The interference between these radars can be zero by adopting orthogonal codes. 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, where $X_0 = 0.5\lambda$ is assumed for the center wavelength λ. Note that $X_0 = 0.5\lambda$ was adpted to avoid the ambiguity of DOA(Direction-Of-Arrival) estimation for band-limited scattered signals.

Only the position of the antennas relative to the target object is considered, inverting the problem to be solved to one of estimating the unknown motion of the antennas scanning 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 based radar imaging algorithm has been developed in previous works [3], [6]. 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.

Target shapes are expressed with x, y and the antenna position is $(X, 0)$ on the x axis. These variables are normalized by the center wavelength λ, and the delay time Y is normalized by the center period $T = \lambda/c$ with the speed of light c. The distance Y between a scattering center and the antenna $(X, 0)$ is easily obtained from UWB radar, and we call (X, Y) a quasi-wavefront.

The following equation IBST(Inverse Boundary Scattering Transform) holds:

$$x = X - Y\frac{\mathrm{d}Y}{\mathrm{d}X}, \quad (1)$$

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

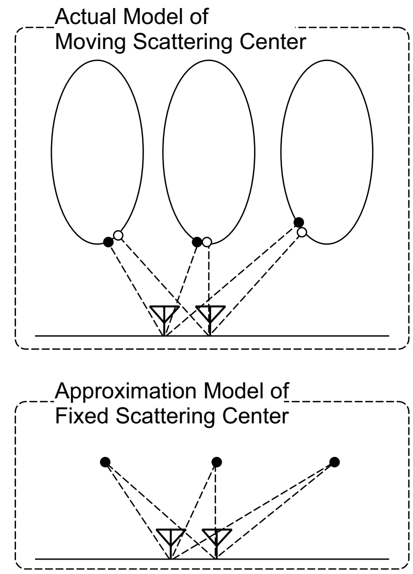

Fig. 3. Actual and approximation models of scattering center.

First, quasi wavefronts are extracted from the received signals $s(X, Y)$ using the SEABED algorithm. Next, the IBST is applied to the quasi wavefronts to obtain the final image.

IV. Observed Data and Imaging Process

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. Under this assumption, the delay times observed with the pair of antennas are

$$Y_1(t) = Y(X(t)), \quad (3)$$

and

$$Y_2(t) = Y(X(t) + X_0) \quad (4)$$

as functions 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. In this problem, a scattering center on a target is not fixed, which makes it difficult to use a conventional interferometric measurement. The actual model and the point-target approximation model are shown in Fig. 3. We cannot adopt this approximation model, and use the follwing method instead.

We proposed an algorithm to estimate $X(t)$, which readily leads to the estimation of $Y(X)$ [7]. First, the pair of times

t_1 and t_2 that 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

$$Y(X(\tau(t))) = Y(X(t) + X_0), \tag{5}$$

This, in turn, is equal to the condition $t_1 = \tau(t_2)$. The function $\tau(t)$ approximately satisfies $X(\tau(t)) = X(t)+X_0$. We derived the following approximation:

$$\frac{\mathrm{d}X}{\mathrm{d}t} \simeq \frac{X(\tau(t)) - X(\tau^{-1}(t))}{\tau(t) - \tau^{-1}(t)} = \frac{2X_0}{\tau(t) - \tau^{-1}(t)}. \tag{6}$$

This approximation is similar to the idea of centered difference. Then, an integration is performed to estimate $X(t)$ as

$$X(t) \simeq \int \frac{2X_0}{\tau(t) - \tau^{-1}(t)} \mathrm{d}t, \tag{7}$$

Finally, the quasi-wavefront $Y(X)$ is calculated using the estimated $X(t)$ with Eq. (3). The target shape can be obtained by applying IBST to the estimated quasi-wavefront.

A. Measurement of Walking Motion

Real walking motion should be used for any feasibility study of the method because the walking motion model is critical for the motion estimation process. To measure real walking motion, we use a video camera in a measuring site, where the walking course is a straight line and the distance to the camera is set to 6.5m. Fig. 4 shows a picture of the site used for measurement and some snapshots of a walking man are displayed. The top point of the head is detected with simple image processing.

1) The background image is recorded as a reference image.
2) A walking human is recorded as a movie with a camera.
3) The reference image is subtracted from the recorded movie images.
4) The image is binarized.
5) The boundary of the image is enhanced with a Laplacian filter.
6) A Gaussian LPF (Low-Pass Filter) is applied for smoothing.
7) The maximum point is detected as the top of a head.

In this experiment, three examinees were instructed to walk naturally straight forward from the left of the area depicted to right. The correlation length of the LPF is set to 0.1m, which was empirically chosen.

Data obtained from a walking motion in this experimental setup is shown in Fig. 5. This figure shows that the measured walking motion is close to uniform. A straight line $x_{\mathrm{s}}(t) = v_0 t + x_0$ is determined by LMS (Least Mean Square) fitting, and this straight line is subtracted from the real walking motion. The remaining, minute, fluctuation component $\Delta x(t) = x(t) - x_{\mathrm{s}}(t)$ is shown as the dashed line in Fig. 6. Because this fluctuation component contains quantization noise, an LPF is applied and the result $\Delta x_{\mathrm{s}}(t)$ is shown as the solid line in Fig. 6. The period of the fluctuation is about 0.5sec and is almost synchronized with the walking steps.

Fig. 4. Experimental site for measurement of walking motion.

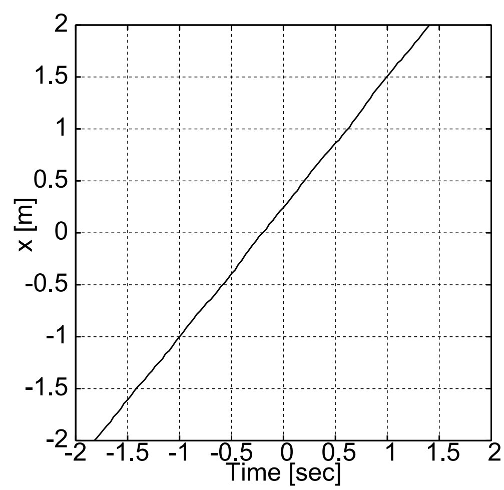

Fig. 5. Measured walking motion.

V. Application of the Proposed Algorithm

A real walking motion is depicted in Fig. 6. We investigated the performance of the proposed method using this experimental data. The approximated solid line in Fig. 6 and the determined regression line are used as a realistic walking motion model as $x_{\mathrm{s}}(t) + \Delta x_{\mathrm{s}}(t)$. It is assumed that the true target shape is an ellipse as shown in Fig. 2.

It was confirmed that the estimated walking motion is almost accurate as in Fig. 7. In this figure, the solid line and dashed line show the estimated and true motion, respectively. The estimation error is shown in Fig. 8. This figure shows that the estimation error is a few centimeters at most. Fig. 9 shows the estimated target shape for the realistic walking model. Although the estimated image has some error points, the entire target shape is estimated quite accurately by the proposed method.

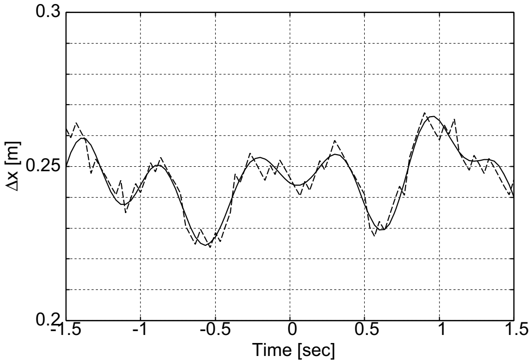

Fig. 6. Fluctuation component of real walking motion.

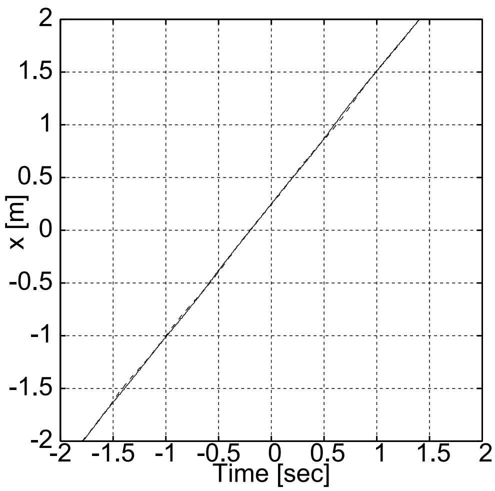

Fig. 7. Estimated walking motion with experimental data.

Future studies should investigate the performance of our algorithm in noise and clutter-rich environments. It is also an important future work to improve the imaging quality by more effectively utilizing the motion estimated.

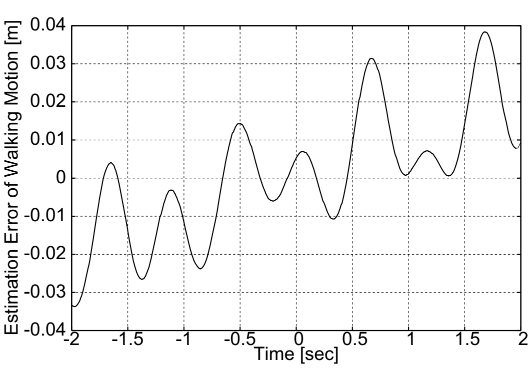

Fig. 8. Estimation error of walking motion with experimental data.

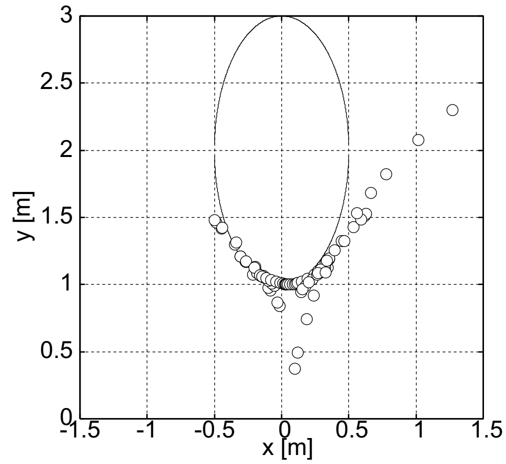

Fig. 9. Estimated target shape with experimental data.

VI. Conclusion

This paper discusses an application of a UWB radar imaging for 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. We use an approximation of the derivative of the walking motion as a function calculated against observed data, and used this to show the efficacy of the algorithm for walking motion. We measured a real walking motion and determined a realistic walking model. Using this realistic model, the performance of the proposed method was investigated. The result shows that the method can estimate a target shape with good accuracy except at some error points. Performance analysis of the proposed algorithm for arbitrary walking motion including meandering and zigzag motion models is an important future task.

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