AN EXPERIMENTAL STUDY ON A FAST AND ACCURATE 3-D IMAGING ALGORITHM FOR UWB PULSE RADAR SYSTEMS

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ABSTRACT

A UWB pulse radar is promising as an environment measurement method for household robots and rescue robots. SEABED algorithm, one of the radar imaging algorithms, can estimate 3-D target shapes in a short time, which cannot be accomplished by conventional algorithms. However, the estimated image of SEABED algorithm has a systematic error even in a noiseless environment, which is caused by the difference between the transmitted waveform and received waveform. In the paper, we quantitatively evaluate the accuracy of SEABED algorithm, and investigate the relationship between the error and the distance to the target. We show the application result for both of a numerical simulation and an experiment.

INTRODUCTION

It is hoped that rescue robots save human lives in the near future. The UWB(Ultra Wide Band) pulse radar is a promising candidate for the environment measurement for robots because they have high range resolution. Radar imaging is known as one of ill-posed inverse problems, for which various algorithms have been proposed. Synthetic aperture method [1, 2] is one of them, which is stable, but its resolution is limited to half the wavelength. Migration algorithm is often used for seismic investigation, which was expanded to apply to a radar imaging [3]. Algorithms using the domain integral equation were also studied [4, 5, 6], which utilize grids with unknown permittivity as a target model. The discrete model fitting method [7] approximates the target boundary by using a set of point targets. These algorithm requires too long calculation time because most of them are based on iterative methods, which is not acceptable for the realtime operation of robots.

We have already proposed a fast imaging algorithm SEABED for UWB pulse radars [8], which can estimate target shape in a remarkably short time. The performance of this algorithm has been investigated only with ideal numerical simulations [9], which does not contain the waveform distortion by the scattering. In this paper, we study this algorithm with realistic numerical simulations with FDTD method and experiments. Additionally, we quantitatively study the accuracy of SEABED algorithm for both of the numerical simulation and the experiment.

SYSTEM MODEL AND SEABED ALGORITHM

We assume a mono-static radar system in this paper. An omni-directional linear-polarization antenna is scanned on a plane. UWB pulses are transmitted at a fixed interval and received by the same antenna. The received data is A/D converted and stored in a memory. We assume that each target is surrounded by a clear boundary. We express real space with the parameter (x, y, z). These parameters are normalized by the center wavelength λ. $s'(X, Y, Z)$ is the received signal at the antenna location $(x, y, z) = (X, Y, 0)$, where we define Z with time t and speed of the radiowave c as $Z = ct/(2\lambda)$. We normalize X, Y and Z by λ. We apply a matched filter of transmitted waveform to $s'(X, Y, Z)$. We define $s(X, Y, Z)$ as the output of the filter. We define a quasi-wavefront $Z(X, Y)$ which is a equi-phase surface extracted from $s(X, Y, Z)$.

SEABED algorithm is based on a reversible transform BST and its inverse transform IBST. IBST describes the target shape (x, y, z) by using the quasi-wavefront (X, Y, Z) as

$$\left\{ \begin{array}{rcl} x & = & X - Z\partial Z/\partial X \\ y & = & Y - Z\partial Z/\partial Y \\ z & = & Z\sqrt{1 - (\partial Z/\partial X)^2 - (\partial Z/\partial Y)^2}. \end{array} \right. \tag{1}$$

This transform is called IBST (Inverse Boundary Scattering Transform). We can obtain the target image by calculating the right-hand side of Eq. (1).

NUMERICAL SIMULATIONS

Fig. 1 shows the estimated target shape by applying SEABED algorithm to the numerical data with FDTD method, where the true target shape is a U-shape metallic object. The upper side of the target is estimated because the antenna is scanned over the target. The entire computation time is 13msec with a single Xeon 2.8GHz processor. Fig. 2 shows the difference between the estimated image and the true image. The true shape is the same as the estimation by an ideal numerical simulation [9]. The averaged error of the image is 4.4×10^{-2} wavelength. The error is large in the region where the antenna is close to the target because the received signals are influenced by the near field. This systematic error is caused by the matched filter applied to the received signal, which is matched for the transmitted waveform, not for the received waveform. Fig. 3 shows the relationship between Z and the error of Z. Each cross symbol in the figure is Z for each (X, Y).

In order to suppress this systematic error, we replace Z by $Z - a\exp(-bZ)$ in Eq. (1), where the parameters $a = 0.154$ and $b = 1.08$ are determined by the least-mean-square-error criteria. The solid line in Fig. 3 is the optimized curve of $Z - a\exp(-bZ)$. Fig. 4 shows the error of the estimated image with this compensation. The averaged error of the proposed compensation is 1.6×10^{-2} wavelength.

EXPERIMENT

We show an application example of SEABED algorithm to an experimental data. We set a metallic pipe with the radius of 92mm (1.2λ) and the length of 1m as a target object. Fig. 5 shows the experimental site, where we see the pair of antennas installed at a 2-D scanner over a metallic cylinder. These antennas are located close to each other, which can be approximately regarded as a mono-static radar system. The transmitted UWB pulse has the center frequency of 3.7GHz ($\lambda = 81$mm) and the bandwidth of 1.0GHz. The antenna transmits pulses at 23×23 positions with intervals of 10mm (0.12λ). The obtained signals has S/N of 20dB after coherent integration. Fig. 6 shows the true target shape for this experiment. Fig. 7 shows the estimated target shape by applying IBST to the extracted quasi-wavefront. Here, we apply the image stabilization algorithm proposed in [10], which is required because IBST requires the 1st order derivative of a quasi-wavefront which is sensitive to noise.

Fig. 8 shows the error of the estimated image. The averaged error of the image is 4.8×10^{-2} wavelength, which corresponds to about 4mm for our experiment. The distance from the antenna changes along the y axis. The error is large at the edges of the estimated image. We have to note that this error can be affected by the stabilization algorithm applied above. The error can also include the error in the alignment of the target pipe and the antenna. Further study is needed to clarify the cause of the estimation error.

CONCLUSION

In this paper, we investigated the estimation error of a fast radar imaging algorithm, SEABED algorithm, with a numerical simulation of FDTD method and an experiment. The averaged error of the estimated image with a numerical simulation and an experiment are 4.4×10^{-2} wavelength and 4.8×10^{-2} wavelength (4mm), respectively. We investigated the systematic error for the numerical simulation, which is caused by the difference between the transmitted waveform and the received waveform. We studied a simple compensation method of this error by replacing the estimated range Z by the approximation function of Z. This simple method does not spoil the advantage of the quick imaging of SEABED algorithm due to its simple procedure. The estimation accuracy was improved to 1.6×10^{-2} wavelength.

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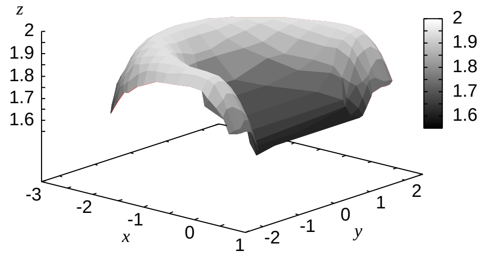

Figure 1: Estimated target shape by SEABED algorithm with FDTD data.

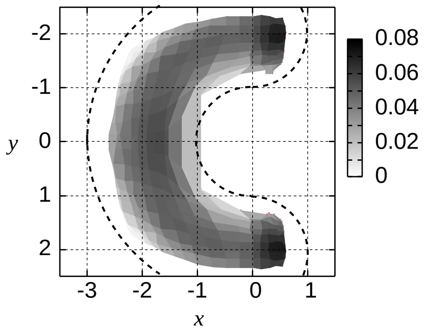

Figure 2: Estimation error of SEABED algorithm with numerical data.

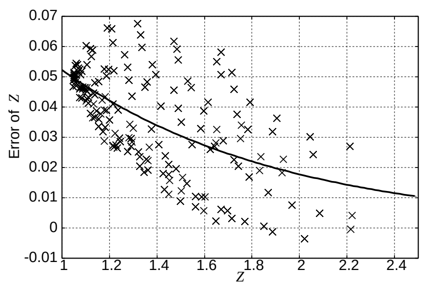

Figure 3: The relationship between Z and its error.

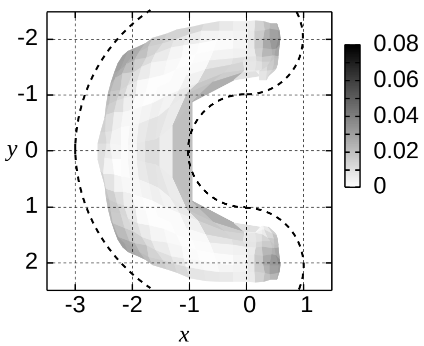

Figure 4: Estimation error of SEABED algorithm with a simple calibration.

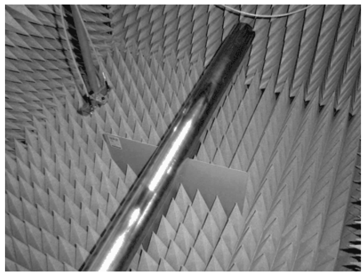

Figure 5: Experimental site of the UWB pulse radar system.

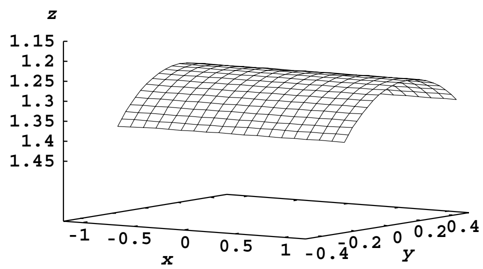

Figure 6: True target shape for experiment.

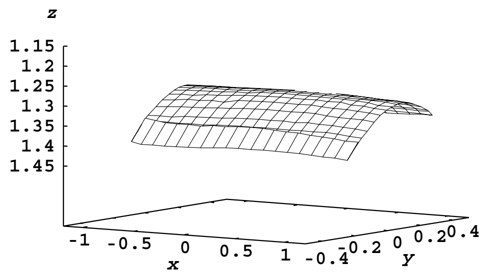

Figure 7: Target shape estimated with experimental data.

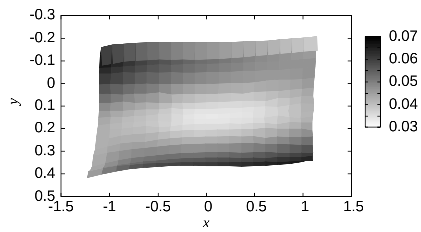

Figure 8: Estimation error of SEABED algorithm with numerical data.