Code-Division Multiple Transmission for High-Speed UWB Radar Imaging with Array Antennas

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INTRODUCTION UWB(Ultra-Wide Band) radars are promising as a high-resolution 3-D imaging technique for nearby targets. We have developed the high-speed imaging algorithm, SEABED algorithm, for UWB pulse radars, which is a key technology for the realtime imaging [1, 2]. However, the antenna scanning for data acquisition takes a long time compared to the SEABED algorithm itself, which is a serious problem for the application to the realtime operations [3]. In this paper, we utilize PN (Pseudo Noise) sequences as the transmitted waveforms, while the original SEABED algorithm assumed impulsive short-wave pulses. We adopt the Gold sequences whose cross-correlations are low, which enables us to simultaneously transmit signals with multiple antennas. In this paper, we show that the proposed radar system achieves a high-speed imaging including the measurement and signal processing.

BOUNDARY SCATTERING TRANSFORM We assume a radar system with array antennas as in Fig. 1. The antennas are omni-directional. We assume M transmitting antennas and one receiving antenna. We simultaneously transmit the PN sequence allocated to each transmitting antenna and receive the echoes by the receiving antenna. We adopt Gold sequences as the PN sequences. We transmit the baseband UWB PN signals without a carrier. The received signal is A/D converted and stored into a memory. We deal with the 2-dimensional system with TE mode waves for simplicity. The assumed targets have clear boundaries with almost uniform permittivity. We express the real space with (x, y) in the x-y coordinate. Here, x and $y > 0$ are normalized by the center wavelength of the transmitting signal λ. We assume that the receiving antenna is at the origin $(x, y) = (0, 0)$, and transmitting antennas are on the x axis. We apply the matched filter of the PN sequence for the transmitting antenna at $(x, y) = (2X, 0)$ to the received data, and we define $s(X, Y)$ as the output signal of the filter. Here, we define Y with time t and the speed of the radiowave c as $Z = ct/(2\lambda)$. It should be noted that the received data is expressed with (X, Y), and target shapes are expressed with (x, y). We define a data space as the space expressed by (X, Y). We normalize X by λ and Y by the chip duration of the PN signals. The point (x, y) in the real space is expressed with (X, Y) as

$$x = \frac{(X^2 + Y^2)\dot{Y} - 2XY}{X\dot{Y} - Y}, \tag{1}$$

$$y = \left|\frac{Y^2 - X^2}{Y - X\dot{Y}}\right| \sqrt{1 - \dot{Y}^2}, \tag{2}$$

which is called IRBST(Inverse Revised Boundary Scattering Transform). We apply this inverse transform to the quasi-wavefronts extracted from the received signals, and obtain the radar image.

PERFORMANCE EVALUATION WITH NUMERICAL SIMULATION In this paper, we adopt Gold sequences for the spread spectrum, with 11th order

LFSR(Linear Feedback Shift Register)s as in Fig. 2. We assume that all the initial values of the LFSRs equal to 1, the code length is 2047, and the number of codes is 2049. The i-th Gold sequence is generated as $G_i[n] = M_1[n] + M_2[n+i]$ with the preferred pair of M-sequences. The 18 kinds of Gold sequences $G_0, G_1, \cdots, G_{17}$ are assigned to 18 transmitting antennas. Fig. 3 shows the output of the matched filter for the sequences assigned to the transmitting antennas. The signals do not contain any noise in this simulation. The random component in the background is caused by the range sidelobe of the auto-correlations and cross-correlations of Gold sequences. We see that the range sidelobes are uniformly distributed. The first echo in each signal is the direct wave, which is the waves directly received from the transmitting antenna. We extract a quasi-wavefront by sequentially connecting the peaks of the echoes. We finally obtain the estimated image as the plots in Fig. 4 by applying the IRBST to the extracted quasi-wavefront. The solid line in this figure is the assumed true target shape. The estimation error is large, which is caused by the range sidelobes of the direct waves because the direct waves have a relatively large power compared to the echoes.

OPTIMIZATION OF SEQUENCES FOR ARRAY RADAR SYSTEM

In this section, we search for suitable sequences in order to suppress the sidelobes of the direct waves. The receiving timing of each sequences is fixed because the distance between the transmitting and receiving antennas is fixed. Our objective is to find the set of sequences whose range sidelobes of the direct waves cancel each other. This process is similar to the pair of complimentary sequences which cancel the sidelobes of the auto-correlation functions. We select suitable 18 sequences among 2049 types of Gold sequences. Additionally, we select a suitable time shift of each sequence because we can arbitrarily select the transmitting timing. We suppress the sidelobes only in the area near the antennas because we do not necessarily have to suppress all the sidelobes. The SEABED algorithm does not work for targets located far from the antennas because the locations of the scattering centers are almost independent of the position of antennas. Therefore, we only estimate the distance to the target instead of the shape although in the far field.

We set the evaluation function to select the sequences as

$$\text{minimize}_{\boldsymbol{c}_1,\boldsymbol{c}_2,\cdots,\boldsymbol{c}_M} \sum_{m=1}^{M} \sum_{l=1}^{L} \left\{ \sum_{n=1}^{M} r_{m,n}(l) \right\}^2 , \tag{3}$$

where $r_{m,n}(l)$ is the cross-correlation function of sequences $\boldsymbol{c}_m$ and $\boldsymbol{c}_n$, M is the number of sequences (or transmitting antennas), L is the number of chips where the sidelobes are suppressed. We set $M = 2049$ and $L = 9$ for the assumed radar system in this paper. For example, if we set the chip rate as 2.5Gchip/s, this optimization suppresses the range sidelobes within about 1m from the antennas. We have to calculate the evaluation function $T_{\text{cal}} = {}_{2049}C_{18} \cdot 2047^{18}$ times in order to check all the possible combinations of Eq. (3). This calculation needs about 10^{93} years with a single processor of Xeon2.8GHz, which is not realistic. Therefore, we find sub-optimum solutions instead of the global solution. In this paper, we adopt the greedy algorithm for the optimization, which sequentially optimizes each variable [4].

Fig. 5 shows the relationship between the evaluation value and the number of calculations of the value in Eq. (3). We show the results of the linear search and the greedy algorithm. The result shows that the greedy algorithm is effective for our optimization problem. The greedy algorithm suppresses the normalized sidelobe level to about 16% compared to the arbitrarily chosen sequences. As a result, we can improve the S/I(Signal-to-Interference Ratio) by 8dB by adopting the optimized sequences.

We investigate the imaging performance of the proposed radar system with the proposed sequences. Fig. 6 shows the echoes and the direct waves with the proposed sequences. We clearly see the peaks of the the echoes compared to Fig. 3, which shows the improvement of S/I. Fig. 7 shows the estimated image with the proposed sequences. The accuracy of the estimation is improved compared to the image with the conventional sequences in Fig. 4.

CONCLUSIONS In this paper, we introduced PN signals with Gold codes instead of the conventional short pulse for the UWB radar imaging, which enabled us to simultaneously transmit signals with multiple antennas. This radar system can obtain the observation data within a short time, which does not spoil the advantage of the high-speed imaging by the SEABED algorithm. We have derived the revised SEABED algorithm in order to deal with the antenna arrangement with a fixed receive antenna and multiple arrayed transmit antennas. This proposed radar system is suffered from the range sidelobes due to the auto-correlations and cross-correlations between PN codes. We found a sub-optimum set of sequences to suppress the range sidelobes. The quality of the estimated target image with the proposed sequences is high enough for most of applications.

References

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[4] T. H. Cormen, C. E. Leiserson and R. L. Rivest, "Introduction to Algorithms, Second Edition," McGraw-Hill, Inc., Sep. 2001.

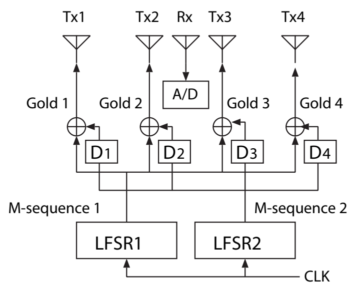

Figure 1: Block diagram of the proposed UWB radar system.

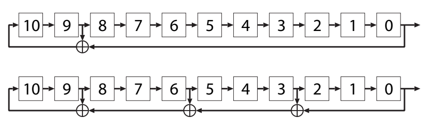

Figure 2: Assumed linear feedback shift registers.

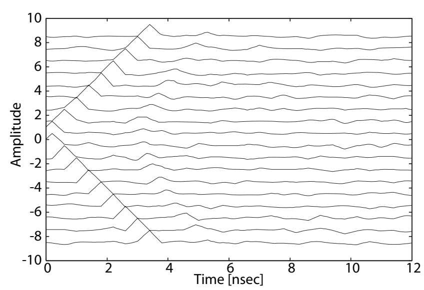

Figure 3: Received signals with conventional codes.

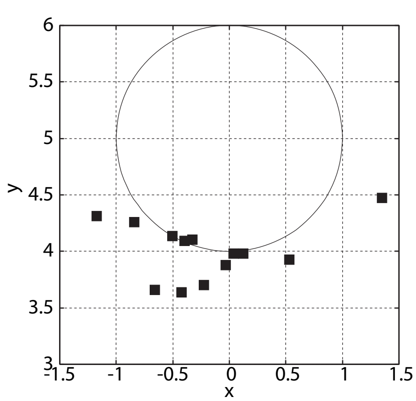

Figure 4: Estimated image with conventional codes.

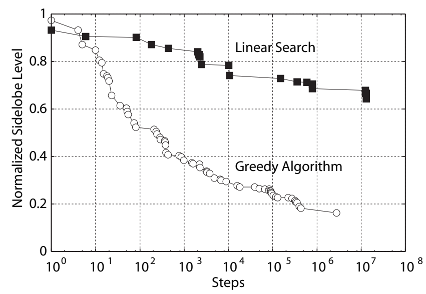

Figure 5: Normalized sidelobe level vs. calculation steps.

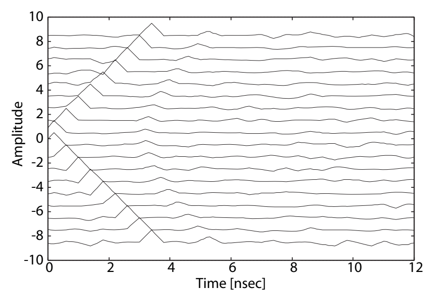

Figure 6: Received signals with the proposed codes.

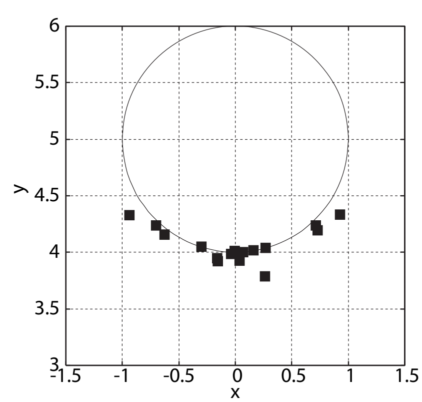

Figure 7: Estimated image with the proposed codes.