Incorporation of Super-resolution Doppler Analysis and Compressed Sensing Filter for UWB Human Body Imaging Radar

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***Abstract*—This paper proposes the range points migration (RPM) based human body imaging method for short range ultra wideband (UWB) radar, which is suitable for the applications such as collision avoidance in autonomous driving system. The performance of the RPM imaging relies on the pre-signal processing, such as Doppler velocity analysis or range extraction. As a promising solution for such the Doppler and range extraction, this paper incorporates with the kernel estimator based Doppler analysis and compressed sensing (CS) based range estimation, which are particularly promising for the lower frequency band UWB radar. Numerical tests demonstrate that our proposed method remarkably enhances the accuracy of the RPM-based imaging due to super-resolution feature of Doppler and range analysis.**

***Index Terms*—Range points migration (RPM) method, Pulse Doppler-radar, Human body imaging, Compressed sensing.**

I. INTRODUCTION

In recent years, an auto collision avoidance technique, recognizing the human body or artificial objects, is strongly demanded especially as the imaging sensor of self-driving system. One promising solution for the above sensor is microwave or millimeter wave radar, which is applicable to optically poor environment $e.g.$ thick smoke and through-the-wall situation in rescue scene. For these applications, a number of three-dimensional (3-D) imaging algorithms focusing on short-range radars have been proposed, most of which are based on coherent integration of scattered waveform[1]. However, the above methods usually require an expensive computational cost to obtain the full 3-D image and suffer from inaccuracy in reconstructions of objects with continuous boundaries. As a promising alternative, the range points migration (RPM) based method has been developed [2]. The literature [3] revealed that the Doppler velocity based data clustering is promising for accurate and low complexity in the RPM based imaging scenario. However, in the through-the-wall scenario, a lower frequency band ($e.g$ S or C band) radar should be assumed in order to ensure sufficient penetration depth in concrete media. In addition, there is a legal regulation known as the UWB spectrum mask which leads to narrower frequency band. Thus, the resolutions in both Doppler velocity and range estimation are severely limited. As to the Doppler velocity estimation, the traditional Fourier transform based method suffers from a trade-off between the temporal and Doppler velocity resolution, and in dealing with larger fractional band signal, the range walk (RW) effect should be considered to obtain a longer coherent integration time. As a promising solution for the above problem, Setsu *et al*, proposed the kernel based range-τ points conversion. Also, the time-of-arrival (TOA) estimator using sparse regularization, known as compressed sensing (CS) TOA filter is introduced [4] to enhance the range resolution with narrower frequency band. The proposed method incorporates the above super-resolution Doppler and range resolution algorithms, using the Doppler velocity based data clustering. Numerical test, assuming the human body imaging scenario with the C-band radar, demonstrates that our proposed method considerably enhances the imaging accuracy for human body.

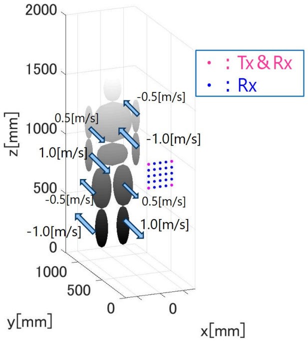


Fig. 1: Observation model.

II. OBSERVATION MODEL

Figure 1 shows the observation model. The array unit is constituted of a number of transmitting and receive antennas. Pulse Doppler radar using multiple transmission sequences with a fixed pulse repetition interval (PRI) is assumed. The locations of the transmitting and receiving antennas are defined as $\boldsymbol{L}_T$ and $\boldsymbol{L}_R$, respectively. For each combination of $\boldsymbol{L}_T$ and $\boldsymbol{L}_R$, electric field is recorded as $s(\boldsymbol{L}_T, \boldsymbol{L}_R, R, \tau)$. Here $R = \mathrm{c}t/2$ is defined using a fast time t and the radio wave speed c. τ denotes given by an integer multiple of PRI.

III. METHOD

The RPM method is based on the Gaussian kernel estimator r for the direction of arrival (DOA)distribution [2]. The literature [3] has introduced the Doppler velocity based range points clustering to reduce the computational complexity and enhance the accuracy in the millimeter wideband radar system. However, in the case of lower frequency band UWB radar, it suffers from a lower resolution of Doppler velocity and range resolution due to narrower frequency band restricted by legal regulation. To address with this issue, this paper incorporates the super-temporal and Doppler resolution method and CS based TOA estimator for the RPM imaging as follows.

A. CS based range estimation

The CS based approach is one of the promising solutions to obtain higher-range resolution without ambiguity responses. Let $\boldsymbol{x}$ the object range profile, $\boldsymbol{n}$ a noise component ,and $\boldsymbol{s}$ the received signal. Here, the object range profile $\hat{\boldsymbol{x}}$ is determined by the following optimization problem:

$$\hat{\boldsymbol{x}} = \arg\min_{\boldsymbol{x}} (\|\boldsymbol{s} - \boldsymbol{A}\boldsymbol{x}\|_2^2 + \lambda\|\boldsymbol{x}\|_1). \tag{1}$$

Here $\|*\|_n$ is defined as l_n norm and λ is regularization factor.

B. Kernel based Doppler velocity estimation

Novel Doppler analysis method has been proposed [5] to overcome the trade-off between Doppler and temporal resolution in the Fourier based analysis. In this method,the range-τ points as $\boldsymbol{q} \equiv (\boldsymbol{L}_T, \boldsymbol{L}_R, R, \tau)$ is extracted from the local maxima of $s(\boldsymbol{L}_T, \boldsymbol{L}_R, R, \tau)$. In the range-$\tau$ distribution, the inclination of adjacent range-τ points corresponds to the Doppler velocity. Focusing on the above, this method determines the optimal Doppler velocity for $\boldsymbol{q}_i$ as;

$$\begin{aligned}\hat{v}_d(\boldsymbol{q}_i) &= \arg\max_{v_d} \sum_j \exp\left(-\frac{|s(\boldsymbol{q}_i) - s(\boldsymbol{q}_j)|^2}{2\sigma_s^2}\right) \\ &\times \exp\left(-\frac{|\tau_i - \tau_j|^2}{2\sigma_\tau^2}\right) \exp\left(-\frac{|v_d - v_{d,i,j}|^2}{2\sigma_{v_d}^2}\right),\end{aligned} \tag{2}$$

where $s(\boldsymbol{q})$ is the signal strength of the amplitude of filter at $\boldsymbol{q_i}$ and σ_s, σ_τ, and σ_{v_d} are empirically determined constants. $v_{\mathrm{d},i,j}$ is defined as $v_{\mathrm{d},i,j} \equiv (R_j - R_i)/(\tau_j - \tau_i)$. As notable feature of this method, Eq. (2) the Doppler velocity optimization defined in Eq. (2) does not require the connecting or tracking of range-τ points, thus greatly reducing the computational cost and avoiding the dependency that occurs in connecting the results.

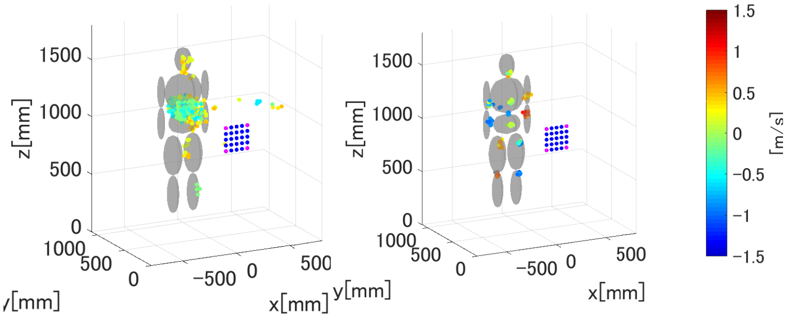
C. Proposed incorporation algorithm

The proposed method incorporates the above algorithms as:

step1) Received signals are processed by CS filtering in Eq. (1) for each slow time τ, and range-τ point $\boldsymbol{q}$ is extracted from local maxima of $s(\boldsymbol{L}_T, \boldsymbol{L}_R, R, \tau)$.

step2) Doppler velocity $\hat{v}_d(\boldsymbol{q}_i)$ is calculated in Eq. (2) for each $\boldsymbol{q}_i$, and is exploited for range-τ clustering.

step3) Clustered set of $\boldsymbol{q}_i$ are processed by RPM, and are converted to a set of scattering center points.



(a)

(b)

Fig. 2: Reconstructed RPM image. (a):Doppler velocity by the method [3]. (b):Doppler velocity by the proposed method.

IV. EVALUATION IN NUMERICAL SIMULATION

Numerical test is presented here, where the received signal is generated by the geometrical optics (GO) approximation, for simplicity. A human body target is approximated as an aggregation of 11 ellipsoids as shown in Fig. 1 5×5 planar array with 50 mm spacing, where 4 transmitters and 25 receivers are assumed, namely, 100 combination data are processed. The transmitting signal forms a pulse-modulated signal with 5.0 GHz center frequency and 3.0 GHz bandwidth. Figures 2 and 3 show the reconstructed RPM image associated with Doppler velocity by the method [3] and the proposed method, respectively. This figure demonstrates that while the former method [3] suffers from a considerable inaccuracy due to insufficient range and Doppler resolution data, the proposed method accurately reconstructs the actual shape of each ellipsoid. Here, the reconstruction error e is introduced as the minimum distance between an actual target boundary and each reconstructed point. The average cumulative probability for satisfying $e \leq 10\,\mathrm{mm}$ is 18.8 % for the method [3] and 97.4 % for the proposed method, respectively.

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