Super-resolution Doppler Velocity Estimation by Gaussian-kernel Based Range-Doppler Conversion for UWB Radar

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Abstract— Through-the-wall imaging (TWI) with ultra-wideband (UWB) radar is promising as the three-dimensional imaging sensor, for detecting human body buried in collapsed walls in rescue scenario. The pulse-Doppler radar is suitable for the above applications, where the Doppler velocity is exploited as human body recognition or motion estimation. Since, in the TWI scenario, the center frequency of the transmitted pulse should be low to maintain an enough penetration depth in a concrete wall, it suffers from an insufficient Doppler frequency resolution in using the Fourier transform based conversion. In addition, the received signal with larger fractional bandwidth could not be overlapped from first and last pulse hit if a long observation time is available, then the Fourier transform based Doppler analysis is not suitable for dealing with the above case. To overcome such difficulty, this paper proposes the Gaussian-kernel based conversion algorithm from extracted range-τ (τ denotes slow time) points to their corresponding Doppler velocities. The finite-difference time-domain (FDTD) based numerical simulation demonstrates that our proposed method simultaneously improves the Doppler velocity resolution and temporal resolution.

1. INTRODUCTION

Microwave through-the-wall imaging (TWI) is one of the promising tools for rescue sensor for detecting human body buried in collapsed walls and furnitures, or discovering hostages or counting the number of terrorists in crime scenes. Ultra-wideband (UWB) radar with lower frequency band is one of the solutions for TWI applications, because of its high range resolution and deeper penetration depth in a concrete wall. In addition, the pulse-Doppler UWB radar has some advantages for higher range resolution with Doppler frequency discrimination, or recognition for human bodies from surrounding obstacles. A lot of Doppler-radar approaches introduce the Fourier transform based estimation in the TWI scenario [1, 2]. However, this type of methods requires a higher center frequency of the transmitted pulse or larger total measurement time to maintain a sufficient Doppler frequency resolution. In the typical TWI scenario, the center frequency of the pulse should be lower to accomplish deeper penetration depth in concrete wall with the certain level of thickness, and thus, it suffers from the degradation of Doppler velocity resolution. In addition, in the case of UWB radar with lower frequency, the fractional bandwidth is usually more than 20%, and in such case, the received pulse could not be overlapped from first and last pulse hit, because longer observation time leads to larger motion of human body in the total measurement time, which worsens an effective Doppler velocity resolution. To achieve super-resolution Doppler velocity estimation in UWB-TWI scenario, the literature [3] introduces the use of multiple signal classification (MUSIC) algorithm, where it improves Doppler velocity resolution compared with that obtained by the Fourier transform approach. However, the result of this Doppler velocity estimation could not be associated to the radar image. In the literature [4, 5], the instantaneous Doppler velocity is calculated by the texture angle, which is defined as the ratio of partial derivatives of signal strengths along first and slow directions, to enhance the temporal resolution of Doppler velocity estimation. However, it requires a pixel connection procedure of the texture angles for interfered situations, and this procedure becomes an extremely complicated and computationally expensive if the number of targets increases. Also, due to using the partial derivative operation, it is, in general, sensitive to small fluctuation of signal strengths.

To achieve higher Doppler velocity and temporal resolutions with much faster and simple algorithm, this paper proposes the Gaussian-kernel based conversion algorithm for discrete range-τ points, which are extracted from local maxima of fast and slow time (denoting τ) map of received signal strengths. Each inclination of range-τ point is accurately determined by the neighboring distribution of other range-τ points by the Gaussian-kernel based statistical characterization. This algorithm is inspired by the principle of the range point migration (RPM) method, where the range points are accurately converted to those corresponding scattered center points without a connection process [6]. As a notable feature of this method, it does not require the connecting or tracking procedure of range-τ points similar to the RPM, which greatly accelerates the processing speed and enhances the accuracy for Doppler velocity estimation. In addition, an instantaneous Doppler velocity for each range-τ point is available in this method, that means the higher temporal resolution up to the pulse repetition interval (PRI) is achieved. The results in the finite-difference time-domain (FDTD) based numerical simulations in TWI scenario, demonstrated that our proposed method remarkably enhances both Doppler velocity and temporal resolutions with much simple algorithm.

2. OBSERVATION MODEL AND RANGE-τ POINT EXTRACTION

Figure 1 shows the observation model assumed for the typical TWI situation. It assumes that the k-th target with an arbitrary boundary shape has a variable motion vector $\mathbf{v}_k(t)$. A set of transmitting and receiving antenna with omni-directional directivity is located at $\boldsymbol{L} = (X, Y)$. A rectangular concrete wall with thickness d_w, relative permittivity ε_w and conductivity σ_w is located in front of the antenna. In each observation sequence, a number of pulses are transmitted with a fixed PRI.

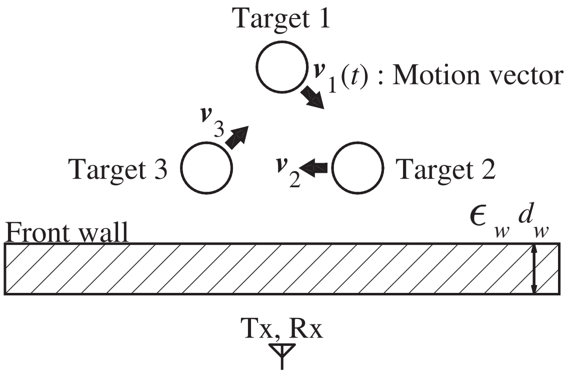


Figure 1: Observation model.

The range-τ signal recorded at the antenna is denoted as $s'(\boldsymbol{L}, \tau', t)$, where t denotes a fast time and τ' denotes a slow time sampled by the PRI. The filter (e.g., matched or Wiener filters) output of $s'(\boldsymbol{L}, \tau', t)$ is denoted as $s(\boldsymbol{L}, \tau', t)$, and converted to $s(\boldsymbol{L}, \tau', R')$ using $R' = ct/2$ with the radio wave speed c in the air. Then, the range-τ point $\boldsymbol{q} \equiv (\boldsymbol{L}, \tau, R)$ is extracted where the following condition is satisfied;

$$\left.\begin{aligned} \frac{\partial |s(\boldsymbol{L}, \tau', R')|}{\partial R'} &= 0 \\ |s(\boldsymbol{L}, \tau', R')| &\geq \alpha \max_{\tau', R'} |s(\boldsymbol{L}, \tau', R')| \end{aligned}\right\}, \tag{1}$$

where α denotes the threshold parameter.

3. PROPOSED DOPPLER VELOCITY ESTIMATION METHOD

To overcome the lower limitation of Doppler velocity estimation in the Fourier transform based analysis, this paper proposes a novel algorithm for Doppler velocity extraction, which is suitable for lower center frequency and larger fractional bandwidth pulse in the UWB-TWI scenario.

Figure 2 shows the relationship among the focused range-τ point $\boldsymbol{q}_i$ and others in the range-τ space. Basically, the inclination to neighboring range-τ points offers the Doppler velocity with given PRI. However, in the case that a sensor receives multiple responses from multiple targets, the range-τ point connection becomes an extremely difficult, and this problem is analogous to joint problem between DOA and range in spatial interferometer scheme, which has been solved by the RPM algorithm [6]. Introducing the RPM based conversion scheme, this method determines the optimal Doppler velocity $\hat{v_{\mathrm{d},i}}$ for $\boldsymbol{q}_i$ as;

$$\hat{v_{\mathrm{d},i}} = \arg\max_{v_\mathrm{d}} \sum_j \exp\left(-\frac{\left|s(\boldsymbol{q}_i) - s(\boldsymbol{q}_j)\right|^2}{2\sigma_s^2}\right) \exp\left(-\frac{\left|\tau_i - \tau_j\right|^2}{2\sigma_\tau^2}\right) \exp\left(-\frac{\left|v_\mathrm{d} - v_{\mathrm{d},i,j}\right|^2}{2\sigma_{v_\mathrm{d}}^2}\right), \tag{2}$$

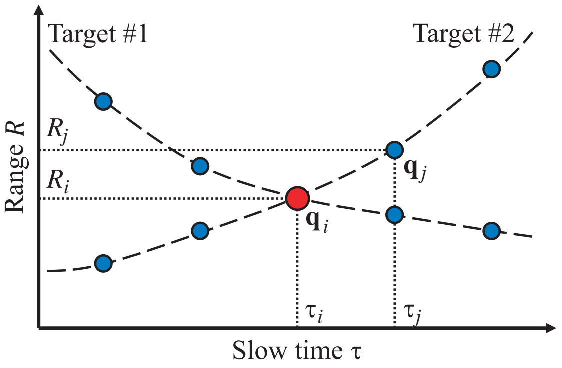


Figure 2: Relationship among the focused range-τ point (red solid circle) $\boldsymbol{q}_i$ and the others (blue solid circles) in the range-τ space.

where s is the signal strength of range-τ point $\boldsymbol{q}$, and σ_s, σ_τ, and $\sigma_{v_{\mathrm{d}}}$ are empirically determined constants. $v_{\mathrm{d},i,j}$ is defined as $v_{\mathrm{d},i,j} \equiv (R_j - R_i)/(\tau_j - \tau_i)$. Eq. (2) assesses the accumulation degree of the converted Doppler velocity points, calculated from all possible combinations of range-τ points, where the slow time interval and signal strength difference are considered in the weighting functions.

This method has some distinguished advantages from the conventional approaches that it remarkably alleviates the lower limitation of both Doppler velocity and temporal resolutions of the Fourier transform based analysis by focusing on the inclination extraction of discrete range-τ points. In addition, the Doppler velocity optimization process in Eq. (2) does not require the connecting or tracking procedure of range-τ points, and greatly reduces the computational cost and avoid the dependency for its connecting result. Furthermore, even in richly interfered case in the range-τ space, it guarantees the accuracy for Doppler velocity estimation, if we obtain well-resolved range-τ responses, and this characteristic is deductive from the RPM method.

The actual procedure of the proposed method is very simple as follows.

Step 1): The received signals are recorded and converted to the range-τ signal as $s(\boldsymbol{L}, \tau', R')$.

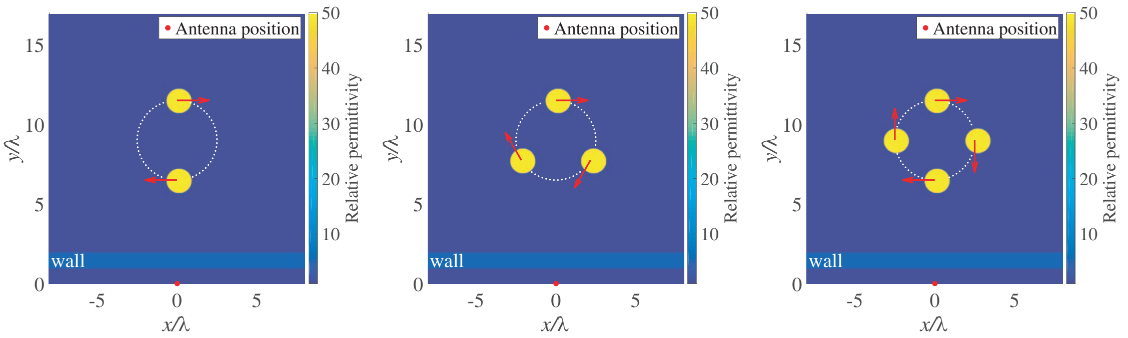
Step 2): The range-τ points $\boldsymbol{q}$ are extracted from local maxima of $s(\boldsymbol{L}, \tau', R')$.

Step 3): The optimal Doppler velocity $\hat{v_{\mathrm{d},i}}$ is obtained in Eq. (2) for each $\boldsymbol{q}$.

4. EVALUATION IN NUMERICAL SIMULATION

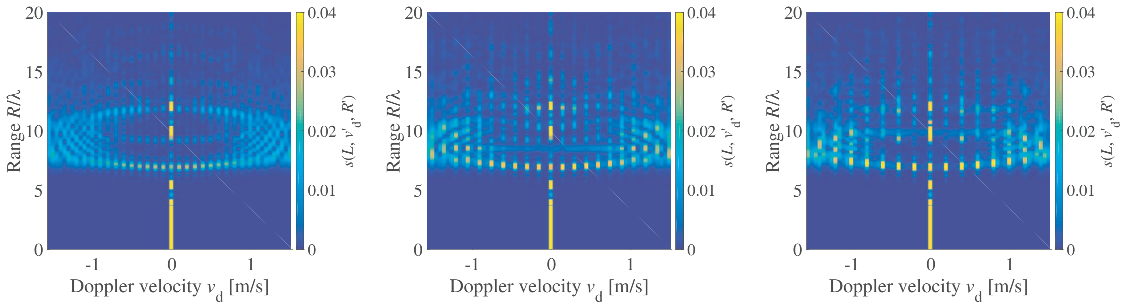
This section shows the performance evaluation in the FDTD based numerical simulation assuming the TWI situation. The transmitting signal forms the Gaussian-modulated sinusoidal pulse, where the center frequency is 3.0 GHz corresponding to the center wavelength of $\lambda = 100\,\mathrm{mm}$, and the effective bandwidth is 2.0 GHz. Both transmitting and receiving antennas are located on the origin. A single rectangular wall is located in front of the antenna with thickness $d_{\mathrm{w}} = 1.0\lambda$, relative permittivity $\varepsilon_{\mathrm{w}} = 5.0$, and conductivity $\sigma_{\mathrm{w}} = 0.005\,\mathrm{S/m}$. Three circle shaped objects (human mimicking), with 50 relative permittivity (assuming non-dispersive and homogeneous) and 1.0 S/m conductivity, rotate along the circular orbit with the origin $(0.0\lambda, 9.0\lambda)$ and the radius 2.5λ. Each object has same velocity as 5.0π m/s and is equally spaced. The observation time is set as $T_{\mathrm{c}} = 0.1\,\mathrm{s}$, which correspond to 0.05 m/s Doppler velocity resolution in the Fourier transform based estimation, and the number of pulse hits is 64. A noise is absent in this case, and the zero-Doppler components are suppressed by removing the average component of $s(\boldsymbol{L}, \tau', R')$ along τ' direction. Here, we test the cases at different number of targets. Case 1 denotes 2 targets, Case 2 denotes 3 targets, and Case 3 denotes 4 targets, respectively. Figure 3 shows the initial dielectric property map in each case.

Figure 4 illustrate the results of the Fourier transform based Doppler-range maps for each case. These results demonstrate that the Fourier transform based Doppler estimation is not suitable in this situation due to an insufficient temporal resolution. It should be also noted that a larger fractional bandwidth signal (e.g., UWB pulse) causes further degradation of Doppler velocity resolution, because the slow time interval of pulse overlapping becomes smaller compared with smaller fractional bandwidth signal. To alleviate the degradation of temporal resolution, one could consider the time-frequency analysis, such as the short time Fourier transform (STFT), however, it has an unavoidable problem for the trade-off between the temporal resolution and the Doppler



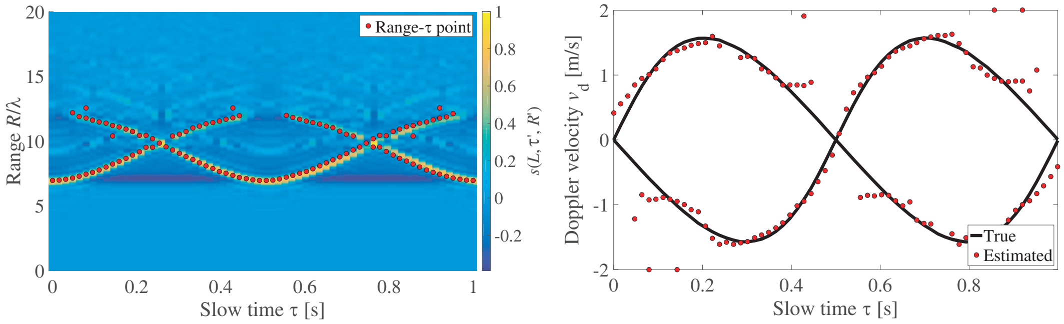
(a) (b) (c)

Figure 3: Initial dielectric maps in each case. Red solid circle denotes the transmitting and receiving antennas' location. (a): Case 1 (2 targets), (b): Case 2 (3 targets), (c): Case 3 (4 targets).



(a) (b) (c)

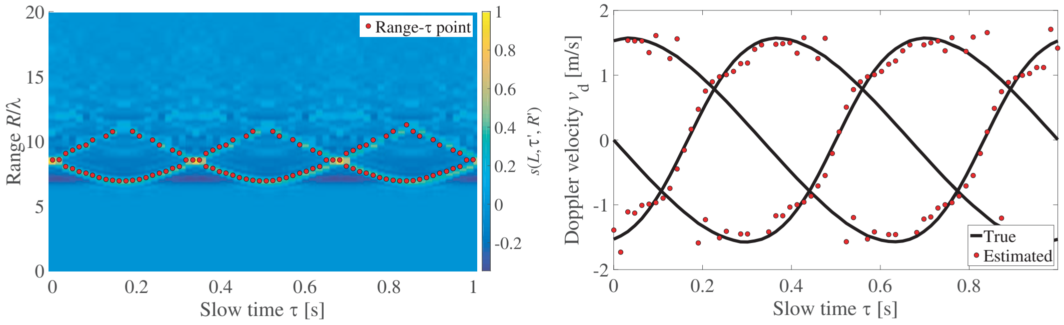
Figure 4: Estimated Doppler velocity by the Fourier transform based analysis. (a): Case 1 (2 targets), (b): Case 2 (3 targets), (c): Case 3 (4 targets).



(a) (b)

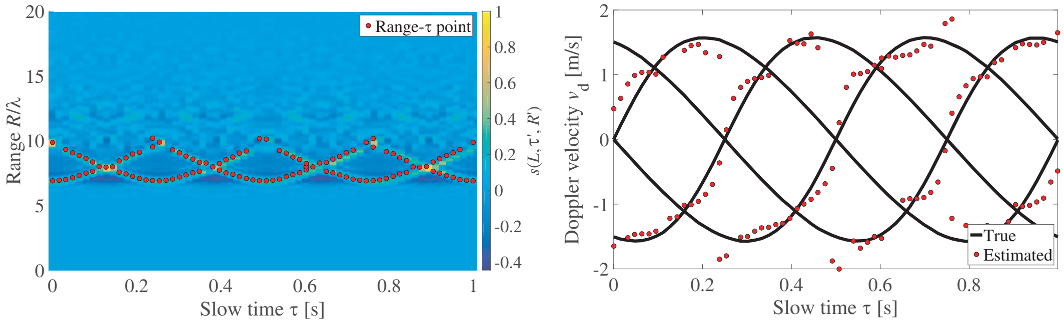
Figure 5: (a): Outputs of Wiener filter and extracted range-τ points. (b): Estimated Doppler velocities (red solid circles) by the proposed method at Case 1.

frequency resolution, and results in the inaccuracy for Doppler velocity estimation, especially in the case assuming a larger fractional bandwidth. On the contrary, Figures 5, 6, and 7 show the observation data and estimation results of the Doppler velocities by the proposed method for Case 1, Case 2, and Case 3, respectively. These results show that the proposed method correctly estimates the Doppler velocity beyond the nominal Doppler frequency resolution at each slow time, namely, the higher temporal and Doppler frequency resolution is available, simultaneously. Note that, the interference at the same range gate incurs inaccuracy for Doppler velocity estimation as shown in these figures. In addition, some Doppler velocities are missed in the estimation, especially in Figures 6 and 7, and this is because an object goes to shadow area of other objects. Note that, the calculation time for Case 1, 2, and 3 is 0.27, 0.18, and 0.21 s, respectively, using Intel Xeon CPU E5-1620 v2 (3.7 GHz) processor with 16 GB RAM, and it is also the advantage of this method, in terms of calculation cost, compared to those requiring connecting or tracking processes.



(a) (b)

Figure 6: (a): Outputs of Wiener filter and extracted range-τ points. (b): Estimated Doppler velocities (red solid circles) by the proposed method at Case 2.



(a) (b)

Figure 7: (a): Outputs of Wiener filter and extracted range-τ points. (b): Estimated Doppler velocities (red solid circles) by the proposed method at Case 3.

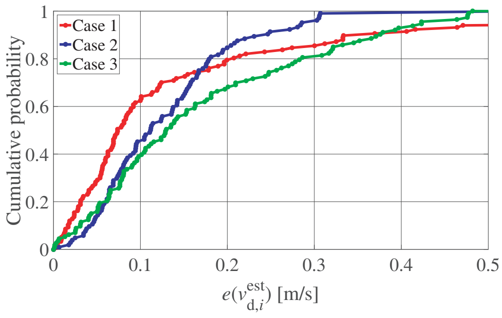


Figure 8: Cumulative probability distribution of the errors for the Doppler velocity estimation in each case.

For quantitative evaluation, the error of the Doppler velocity estimation is defined as;

$$e(v_{\mathrm{d},i}^{\mathrm{est}}) \equiv \min_{v_{\mathrm{d}}^{\mathrm{true}}} |v_{\mathrm{d},i}^{\mathrm{est}} - v_{\mathrm{d}}^{\mathrm{true}}|, \quad (i = 1, 2, \ldots, N_{\mathrm{T}}), \tag{3}$$

where $v_{\mathrm{d},i}^{\mathrm{est}}$ is the estimated Doppler velocity of the i-th range-τ point $\boldsymbol{q}_i$, $v_{\mathrm{d}}^{\mathrm{true}}$ are the true Doppler velocities at each slow time snapshot, and N_{T} is the total number of $v_{\mathrm{d},i}^{\mathrm{est}}$. Figure 8 shows the cumulative distribution of $e(v_{\mathrm{d},i}^{\mathrm{est}})$ for each case. The cumulative probabilities satisfying $e(v_{\mathrm{d},i}^{\mathrm{est}}) < 0.2\,\mathrm{m/s}$ is 79.5% for Case 1, 84.6% for Case 2, 67.3% for Case 3. This quantitative evaluation shows that our proposed method accurately estimates the Doppler velocities of multiple targets in TWI scenario.

5. CONCLUSION

This paper proposed a novel algorithm for super-resolution Doppler velocity estimation in the UWB-TWI scenario. The proposed method introduces the Gaussian-kernel based conversion algorithm for range-τ points to the Doppler velocity points without any connecting or tracking procedures. The FDTD-based analysis, which assumed the UWB-TWI scenario, demonstrated that the proposed method accurately estimated the Doppler velocities of multiple target models with considerably higher temporal resolution. Note that, this method does not require the phase information of each received pulse, and it is our future work to incorporate this method with suitable imaging algorithm such as RPM method.

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REFERENCES

1. Kidera, S., Y. Sasaki, S. Fang, T. Kirimoto, K. Saho, and T. Sato, "Accuracy enhanced RPM method using doppler based range points clustering for 140 GHz band UWB Radar," *Proceedings of International Symposium on Antennas and Propagation (ISAP)*, 628–629, Okinawa, Japan, October 2016.
2. Bujakovi, D., M. Andri, D. Mikluc, and B. Bondnuli, "Analysis of human radar echo signal using warped discrete Fourier transform," *Proceedings of New Trends in Signal Processing (NTSP)*, Demanovska Dolina, Slovakia, October 2016.
3. Dawood, M., N. Quraishi, and A. V. Alejos, "Superresolution doppler estimation using UWB random noise signals and MUSIC," *IEEE Trans. Aerosp. Electron. Syst.*, Vol. 49, No. 1, 325–340, 2013.
4. Sakamoto, T., T. Sato, Y. He, P. J. Aubry, and A. G. Yarovoy, "Texture-based technique for separating echoes from people walking in UWB radar signals," *Proceedings of URSI Commission B International Symposium on Electromagnetic Theory (EMTS)*, 119–122, Hiroshima, Japan, May 2013.
5. Sakamoto, T., T. Sato, P. J. Aubry, and A. G. Yarovoy, "Texture-based automatic separation of echoes from distributed moving targets in UWB radar signals," *IEEE Trans. Geosci. Remote Sens.*, Vol. 53, No. 1, 352–361, 2015.
6. Kidera, S., T. Sakamoto, and T. Sato, "Accurate UWB radar three-dimensional imaging algorithm for a complex boundary without range point connections," *IEEE Trans. Geosci. Remote Sens.*, Vol. 48, No. 4, 1993–2004, 2010.