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Envelope Correction of Micro-Motion Targets Based on Multi-Layer Perceptron During THz-ISAR Sensing

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ABSTRACT Translational compensation is one of the key problems in parameter estimation of moving targets and radar imaging, and envelope correction is the basis of translation compensation. However, in inverse synthetic aperture imaging, the traditional translation compensation algorithms cannot be applied to micro-motion targets. Based on the characteristics of micro-motion targets and the advantages of the terahertz radar, a new method of envelope correction for micro-motion targets based on the multi-layer perceptron is proposed in this paper, which is verified by a radar system with a carrier frequency of 330 GHz. The experimental targets adopted in this paper are rotating corner reflectors and precession warhead. Finally, this paper proposes a measure based on inverse Radon transform and compares the performance of the proposed algorithm with that of the previous one, which fully verifies the effectiveness of the proposed method.

INDEX TERMS Terahertz radar, envelope correction, multi-layer perceptron, micro-motion, inverse synthetic aperture radar.

I. INTRODUCTION

In radar imaging, translations and rotations are the main components in the motion of targets. The translational components not only shift the high-resolution range profile (HPPR) between slow-time samples, but also introduce additional phase errors which lead to defocus in the azimuth direction [1], [2]. So translation compensation is the key to inverse synthetic aperture radar (ISAR) imaging of non-cooperative targets, and plays an influential role in imaging quality. In the scenario of small-angle imaging, In order to ensure the compensation accuracy, envelope correction and phase compensation are generally considered separately. However, for parameter estimation and imaging of micro-motion targets, such as the rotating antennas, helicopters' rotating rotors and the precession mid-course ballistic targets, range migration is inevitable due to the requirement a long observation time. In this condition, the correlation coefficients among range profiles are severely reduced, which make the traditional envelope correction criteria less effective. In addition, most of the ISAR systems adopt dechirp-on-receive method to acquire the echo signal, and the reference range of radar varies with the movement of the target, which will seriously affect the time delay of range envelope and make it dislocate in the slow time domain.

Up to now, most of the research on envelope correction has been concentrated on ISAR imaging of translation targets in the microwave region. Many scholars have proposed a series of methods and verified them to some extent [3], [4]. However, the research on translational compensation for micro-motion targets is very limited. Typical methods include the following: JQ. Li et al. proposed a novel compensating method for micro-motion targets of rotationally symmetric based on the micro-Doppler symmetry cancellation effect [5]. Nevertheless, on the one hand, this method is only applicable to rotationally symmetric targets. On the other hand, this method is more applicable for synthetic aperture radar processing since a constant the reference range is applied in the simulation. For micro-motion targets with complex motions, WP. Zhang et al. proposed a frequency estimation method based on the combination of piecewise translation compensation and time-frequency squared difference sequences [6] However, this method is only suitable for estimating micro-motion parameters in narrowband

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radar system, and not suitable for imaging in the wideband radar system. In addition, current studies mainly focus on the microwave band, while researches in the terahertz band are in strong demand. Comparing to microwave radar systems, terahertz radar systems operate at a higher frequency range with wider bandwidths. These provide the possibility for high precision parameter estimation and high-resolution imaging [7], [8]. On the other hand, the high range resolution in terahertz imaging raises the requirement of precision in envelope correction [9]. In our previous work, focusing on terahertz ISAR imaging of micro-motion targets, we have put forward an envelope correction method based on second compensation [10]. However, it is not suitable for real-time processing owning to the inherent defeats.

In order to realize real-time translation compensation of micro-motion target, a novel envelope correction method based on multi-layer perceptron (MLP) is proposed, which is especially suitable for the terahertz band. The structure of this paper is as follows: Section II introduces in detail the signal model of the micro-motion target and the envelope correction method based on MLP. In section III, a radar system with carrier frequency of 330 GHz is introduced, and verification experiments for micro-motion targets are carried out. Furthermore, a measurement criterion based on inverse Radon transform (IRT) is proposed to evaluate the performance of the proposed algorithm. The performance of the proposed algorithm is analyzed and compared with that of the previous one. Conclusions are drawn in the last section.

II. ENVELOPE CORRECTION BASED ON THE MLP

A. SIGNAL MODEL AND SIMULATION

The typical micro-motion forms include vibration, rotation and precession. On the basis of ignoring the translation between the target and the radar, the projection of micro-motion on the radar line of sight can generally be regarded as a simple harmonic motion. Therefore, the distance expression of a micro-motion target with K scattering centers can be written as follows:

$$R_k = R_0 + a_k \sin(\omega_k t_m + \varphi_k), \quad k = 1, 2 \ldots K \tag{1}$$

where R_0 indicates the initial distance between the target and the radar. a_k, ω_k and φ_k represent the amplitude, angular velocity and initial phase of the micro-motion scatterer k, respectively. Without losing generality, we assume that the radar transmits a linear frequency modulation (LFM) pulse signal. According to its signal characteristics and the motion of the target [11], the expression of the echo signal of the micro-motion target can be written as follows:

$$s_{if} = \sum_{k=1}^{K} rect\left(\frac{\hat{t}-\tau}{T_p}\right) \exp \times \left[-j\frac{4\pi}{c}\gamma\left(\hat{t}-\frac{2R_{ref}}{c}\right)(R_k - R_{ref})\right] \tag{2}$$

where $\hat{t}$ and t_m indicate the fast-time in range and the slow-time in azimuth, respectively. T_p is the pulse width of the LFM signal. If it is a linear frequency modulated continuous wave (LFMCW) signal, T_p can also be regarded as sweep period. $\tau = 2R_k/c$ is the delay time where c is the light velocity. R_{ref} is the reference range for dechirp receiving procedure (time-dependent in ISAR observation). According to the Fourier expression of Equation (2) at the fast-time in range, the envelope of the range profile sequence can be expressed as:

$$S_{if} = \left| T_p \sum_{k=1}^{K} \sin c\left[T_p\left(f_i + 2\frac{\gamma}{c}(R_k - R_{ref})\right)\right]\right| \tag{3}$$

When the reference distance is kept constant during the observation time, the envelope of range profile for a micro-motion target would be sinusoidal, and the modulation period is consistent with the micro-motion period of the target. However, in the ISAR imaging scene, the normal sinusoidal modulation is obscured by the tracking error of reference distance. This introduces difficulties in parameter estimation parameters and imaging.

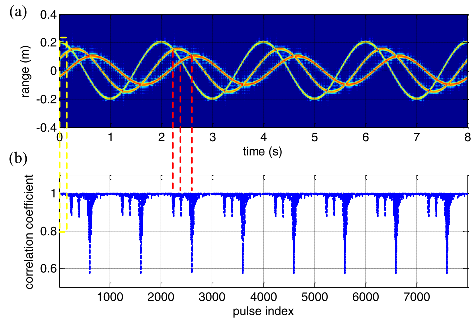


FIGURE 1. (a) HRRP sequence of the rotating scatterers and (b) the adjacent correlation coefficients.

In order to give a more in-depth introduction to the algorithm proposed in this paper, a simulation scenario with three scattering centers is conducted. The carrier frequency in simulation is set to 330 GHz, and the bandwidth is 12 GHz. The rotating radii of the scatterers are set as 0.2 m, 0.15 m and 0.1 m, respectively, and the corresponding normalized scattering intensities are 0.6, 0.8 and 1. The rotating period is 2 s. The HRRP sequence of the rotating scatterers is shown in Fig. 1(a). The sinusoidal modulation is obviously visible because there is no deviation of the reference distance in simulation. However, this is an idealized result for micro-motion targets. In practice, the range profile sequences will shift due to the time-varying reference distance.

Under the condition of small-angle model, the migration through resolution cells can be ignored. Hence, with each resolution cell fixed, envelope correction can be realized by conventional envelope correction methods, such as the cross-correlation method and the minimum entropy method. Although these methods are not applicable for micro-motion targets in the terahertz band, there is still a high similarity between the adjacent range profiles.

The adjacent correlation coefficients of the range profile sequence are shown in Fig. 1(b). It is obvious that most of the correlation coefficients between adjacent range profiles are greater than 0.9. Therefore, in traditional ISAR imaging processing, envelope correction method based on adjacent correlation is also effective for fretting targets. As the core of adjacent correlation algorithms, the shift value of each range bin can be obtained by the following operations:

$$\widehat{\xi} = \arg\left[\max_i\left(\left|S_n^i\right| \cdot \left|S_n^{ref}\right|\right)\right] \quad (4)$$

where $\widehat{\xi}$ is the cyclic shift value based on the adjacent correlation method; $|\cdot|$ is the modules operator of a vector. The n-th range profile S_n can be obtained by taking the previous range profile S_{n-1} as the reference signal S_n^{ref}:

$$S_n^{ref} = S_{n-1} \quad (5)$$

However, the occurrence of jump and drift errors are inevitable in the adjacent correlation methods. Although the cyclic shift value between pulses can be obtained by the adjacent correlation method, the small errors among adjacent range profiles will accumulate and eventually become significant. In addition, the possible abnormal range profiles will destroy the similarity between the adjacent range profiles. The performance of jump error and drift error in range sequence are usually the 'sudden jump' phenomenon and the 'integral decline' phenomenon, respectively. In order to overcome the jump error, we usually adopt the accumulation correlation method. That is to say, the reference pulse is not a pulse before the current pulse, but the average of several pulses before the current pulse. Obviously, this method is not suitable for the micro-motion target, because the correlation coefficient between the current pulse of the micro-motion target and several previous pulses decreases sharply with the increase of the number of pulses.

B. ENVELOPE CORRECTION BASED ON MLP

Artificial Neural Network (ANN) is a kind of learning algorithm based on the biological neural networks. It is based on the understanding and reconstruction of the human brain. After years of development, ANN has been widely used in various fields, such as target classification, pattern recognition, image interpretation and parameter estimation [12], [13]. ANNs are generally divided into forward-structured neural networks, backward-structured neural networks and feedback-structured neural networks according to their network connectivity. MLP is a forward-structured artificial neural network, which can be regarded as a directed graph composed of multiple node layers, each layer connected to the next layer. The trained network can form a non-linear mapping relationship between the input space and the prediction space.

In this paper, error back propagation (BP) algorithm is used to train the MLP. In some literatures, MLP neural network based on BP algorithm is also called BP network, which belongs to the training mode of tutors [14], [15]. In this paper, MLP neural network is used as a predictor, and several pulses before the current pulse are used as input to get the predicted pulse. Then, the maximum correlation between the predicted pulse and the previous pulse and the current pulse is calculated, and the reference pulse is the one with greater correlation. That is to say, for the current pulse, if the correlation between the former pulse and the current pulse is larger, the former pulse is selected to align; otherwise, the MLP prediction pulse is selected as the reference to align. In this way, it is equivalent to adding a reference pulse selection based on the adjacent correlation alignment method, which can effectively solve the jump error and drift error caused by the insufficient correlation of some pulses in the adjacent correlation alignment process. The structure of the MLP neural network established in this paper is shown in Fig. 2. It consists of seven layers, one input layer, one output layer and five hidden layers. The performance evaluation standard is mean square error (MSE).

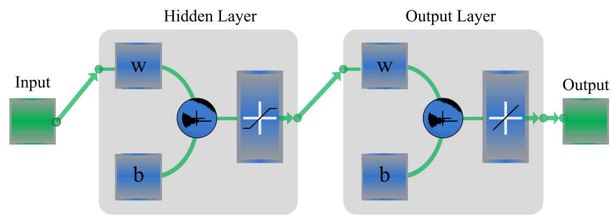


FIGURE 2. Diagram of the MLP neural network adopted in this paper.

In general, each range profile denotes an input sample during the networking training. In the method, the MLP is essentially a kind of predictor. For example, for the current range profile which needs to be adjusted, the input of the MLP should be several range profiles which have been adjusted before the current range profile. The target data is the output of the MLP. In other words, the target data is the predicted data of the MLP with the input of the range profiles. In order to verify the prediction performance of the MLP neural network, a perceptron process output is shown in Fig. 3. The inputs of the network are in the range of pulse indices from No. 1 to No. 99 (the yellow box in Fig. 1), and the current profile to be corrected is at pulse index No. 100. Of all the input pulses, we randomly selected 70% as the training set, 15% as the test set, and the remaining 15% as the verification set. A typical prediction process is shown in Fig. 3. It can be seen from Fig. 3(a) that the neural network reached the optimal state and terminated at the 14th step, and the MSE of the network is 5.71×10^{-4}. At this moment the network training set, the test set, the validation set and the training target all reach their optimal states. In addition, the training method based on cross validation is adopted in this paper to avoid over-fitting problem of the network. It is obvious that from Fig. 3(b) that the training stops when the validation set errors rose for 6 times. Fig. 3(c) is the performance validation of the network. R denotes the correlation coefficients between the predication value and the real value. The closer R reaches 1, the better the performance of the network becomes. The correlation coefficients in this prediction process are all

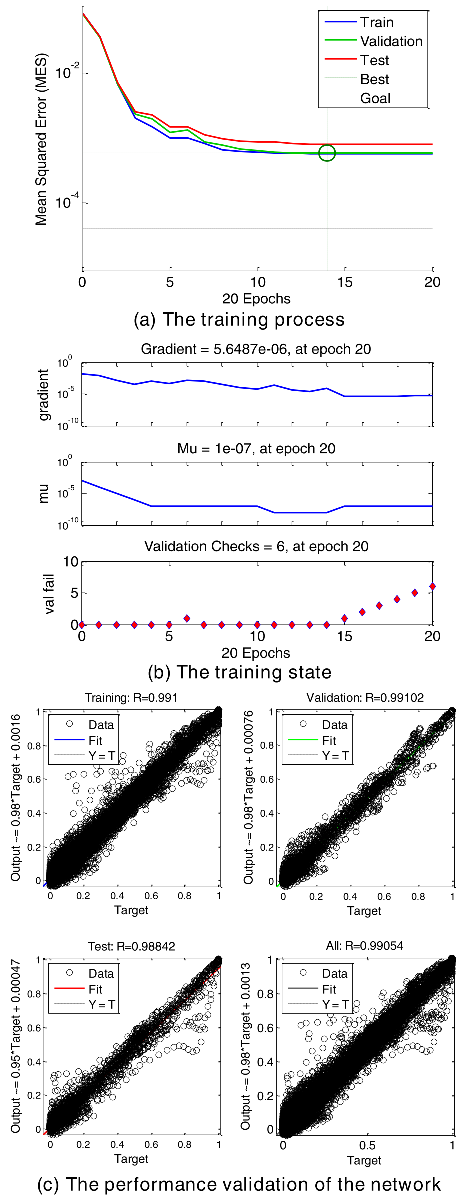


FIGURE 3. A prediction process based on MLP.

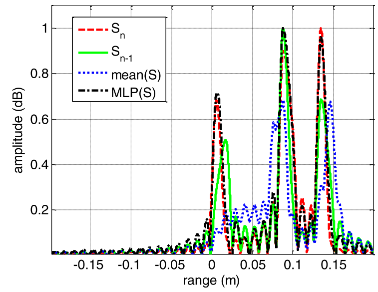


FIGURE 4. Results of a prediction process based on MLP.

greater than 0.98, proving the excellent performance of the MLP network established in this paper.

After obtaining the output of the MLP network, we plot the current profile S_n, the previous profile S_{n-1}, the mean of the accumulation of N-1 profiles $mean(S)$ and the output of the MLP $MLP(S)$ in Fig. 4. The previous profile and the mean of the N-1 accumulation profiles are the reference profiles of the adjacent correlation criterion and the accumulation cross-correlation criterion, respectively.

It is obvious that the output of the MLP has higher similarity to the current profile comparing with S_{n-1} and $mean(S)$ in this prediction process. That is to say, the output of MLP is more suitable as a reference pulse. Of course, such a conclusion is not always valid. Therefore, we establish a criterion to select the appropriate reference pulse. That is to say, we select a reference pulse from S_{n-1} and $MLP(S)$ that has a higher correlation with the current pulse. In this case, the defects of adjacent correlation criteria can be supplemented by MLP, and the jump error and drift error can also be eliminated. The selection criteria of the reference profile for current profile S_n is as follows:

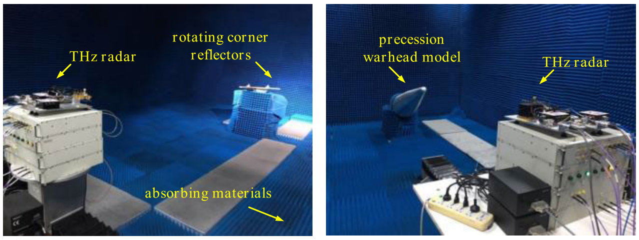
$$S_n^{ref} = \begin{cases} S_{n-1}, & \max\left[\left|S_n^i\right| \cdot \left|S_{n-1}\right|\right] \\ & \quad \geq \max\left[\left|S_n^i\right| \cdot \left|MLP(S)\right|\right] \\ MLP(S), & \max\left[\left|S_n^i\right| \cdot \left|S_{n-1}\right|\right] \\ & \quad < \max\left[\left|S_n^i\right| \cdot \left|MLP(S)\right|\right] \end{cases} \tag{6}$$

In particular, in the simulation, the simulation data were choosing for training the network. In the real data processing, the real data were choosing for training the network. In other words, the network must be trained by the data itself because of the uniqueness of each data. For example, the network must be trained by several range profiles before the current range profile in the same set of data. This requires that the first few range profiles need a pretreatment in advance by other methods, such as the adjacent correlation criterion. That is to say, the method based on MLP is a significant and necessary auxiliary of the traditional methods. It can greatly improve the effectiveness and reliability of the traditional methods.

III. THE EXPERIMENTS AND RESULT ANALYSIS

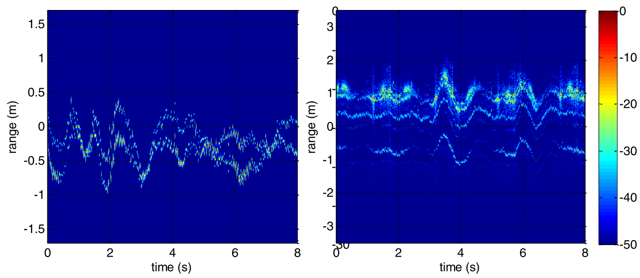
A. THE TERAHERTZ RADAR AND THE EXPERIMENTS

Experiments on the micro-motion targets based on a wide-band terahertz radar imaging system have been implemented to verify the envelope correction method based on MLP. The carrier frequency of the transmitted LFM pulse is 330 GHz and the bandwidth is 10 GHz, providing a theoretical range resolution of 1.5 cm. The output signal is obtained by multiplying a Ku-band signal 24 times, and is finally output by a conical horn antenna. Two sets of experiments on micro-motion targets were designed in this work. In Experiment I, two rotating corner reflectors driven by a motor were implemented for imaging, as indicated in Fig. 5(a). The rotating radii are 0.18 m and 0.32 m, respectively. The rotation period is 4 s. Experiment II focuses on a precessing warhead model, and the precession period is set to 2 s (Fig. 5(b)). The data acquisition time of both experiments is 8 s. In order to reduce the influence of background noise, the targets and radar are placed in anechoic chamber during experiments.



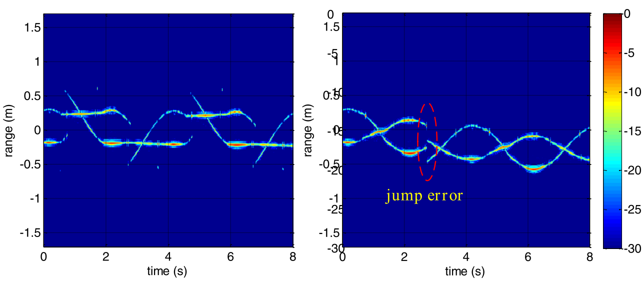
(a) Rotating corner reflectors (b) Precessing warhead model

FIGURE 5. Experimental scenarios of ISAR imaging on micro-motion targets.



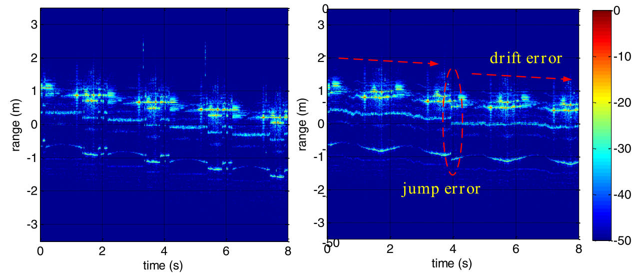
(a) Rotating corner reflectors (b) Precessing warhead model

FIGURE 6. Initial HRRP sequences of micro-motion targets.



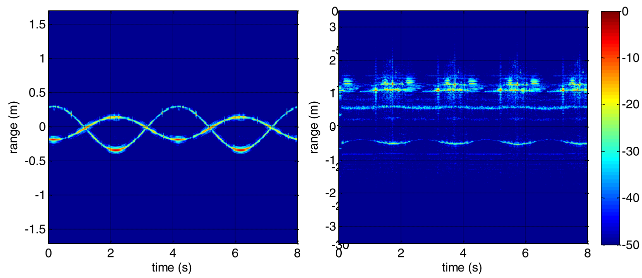
(a) Accumulation cross-correlation criterion (b) Adjacent correlation criterion

FIGURE 7. The HRRP sequences of the rotating corner reflectors after envelope correction based on traditional criteria.



(a) Accumulation cross-correlation criterion (b) Adjacent correlation criterion

FIGURE 8. HRRP sequences of the precessing warhead model after envelope correction based on traditional criteria.



(a) Rotating corner reflectors (b) Precessing warhead model

FIGURE 9. The HRRP sequences of the micro-motion targets based on MLP.

B. THE EXPERIMENTAL RESULTS

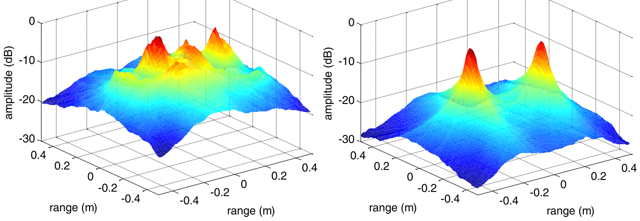
The echo signal is transformed to baseband by down conversion through dechirp processing. After the I/Q demodulator and A/D sampling, the baseband signal is transmitted to PC for further processing. The HRRP sequences of the targets are shown in Fig. 6. Obviously, the HRRP sequences are disordered due to the time-varying of the reference distance and the micro-motion of the targets themself. For the rotating corner reflectors, the range profile sequence is especially chaotic because the trajectories of the two corner reflectors are intersecting in the range direction. For the precessing warhead model, the scattering components corresponding to each part can be separated relatively. But in essence, the trajectories of the scattering components are sinusoidal modulation due to the micro-motion, and the sinusoidal modulation will be destroyed by the time-varying reference range.

In order to realize envelope correction of micro-motion targets, the traditional criteria mentioned in Section II were tried, and the results are shown in Fig. 7 and Fig. 8, respectively. However, due to the inherent violation of these criteria, the envelope correction performance was poor. The methods based on accumulation cross-correlation criterion have no obvious effects as well because of the correlation coefficients decrease rapidly with the increase of pulse accumulation number. Adjacent correlation criterion has a moderate effect, but it is ineffective against the jump and drift errors. As such, the traditional criteria are not applicable to micro-motion targets, and that is why we propose the method based on MLP.

The results of the method based on MLP are in Fig. 9. Compared with the results of adjacent correlation methods, the HRRPs processed by the MLP algorithm are continuous and sinusoidal modulation, which are also consistent with the actual situation. The results in Fig. 9 demonstrate the effectiveness of the proposed algorithm.

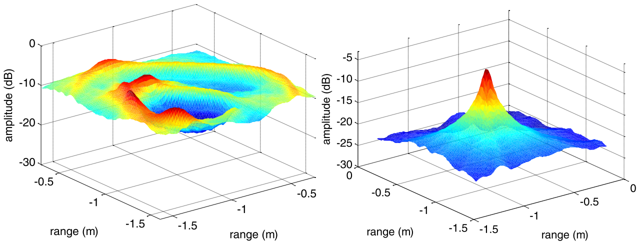
C. PERFORMANCE ANALYSIS OF THE ENVELOPE CORRECTION METHOD

Although the effectiveness of this method had been proved, an evaluation standard is needed to evaluate the performance. However, very few researches have focused on envelope correction for micro-motion targets, and currently there are no standards for evaluating the performance. Therefore, in view of the sinusoidal modulation characteristics of the micro-motion targets, an evaluation criterion based on IRT of the range sequence is proposed in this paper. IRT is a typical method for detecting sinusoidal curves in images. It has been widely used in radar field, including parameter estimation and imaging of micro-motion targets [16], [17]. According to the theory of image reconstruction, IRT can map the sinusoidal curve in the image to the peaks in the parameter space, and the



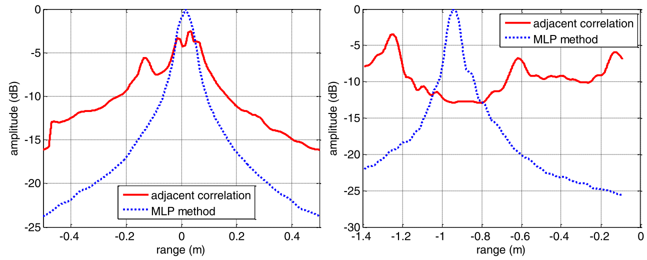
(a) Through adjacent correlation correction (b) Through MLP correction

FIGURE 10. IRT result of the HRRPs of the rotating corner reflectors through different correction methods.



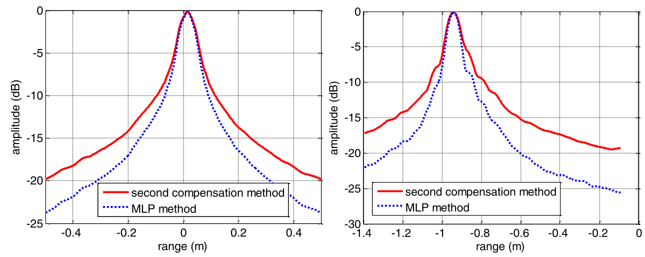
(a) Through adjacent correlation correction (b) Through MLP correction

FIGURE 11. IRT result of the HRRPs of the precession warhead-top through different correction methods.



(a) A corner reflector (b) The warhead-top scatterer

FIGURE 12. Comparison of the focusing performance of the IRT results through different correction methods.



(a) A corner reflector (b) The warhead-top scatterer

FIGURE 13. Comparison of the focusing performance of the IRT results through second compensation method and MLP correction.

parameters and characteristics of the sinusoidal curve directly determine the position and focusing characteristics of the peaks [18].

When IRT is applied, the focusing quality of the peaks in parameter space will deteriorate severely if the sinusoidal curves are discontinuous or declining in amplitude. Therefore, the focusing degree of the peaks formed by IRT transform of the range profile sequence of micro-motion targets can be used as a standard of measurement of envelope correction for micro-motion targets. This paper adopted this standard to measure and compare the effect of envelope correction methods for micro-motion target. The IRT results of the envelope corrected by the adjacent correlation and MLP method are shown in the Fig. 10 and Fig. 11. Comparing to Fig. 10(b), the peaks corresponding to the two rotating corner reflectors are not ideally focused in Fig. 10(a) owning to the discontinuous HRRP sequence in Fig. 7(b). That is to say, the deviation of sinusoidal curve caused by jump error makes this part of sinusoidal curve not contribute to focusing during IRT. In Fig. 11(a), due to the combined effect of jump error and drift error, the IRT of range profile sequence of the warhead top is seriously defocused. On the contrary, it can be seen from Fig. 11(b) that the IRT of the warhead top focuses well after correction based on MLP algorithm The IRT results of the HRRP sequences based on MLP demonstrate the excellent performance of the method proposed in this paper. Furthermore, in order to quantitatively measure the performance of these two algorithms, we plotted the section curves corresponding to the peaks in Fig. 10 and Fig. 11, as shown in Fig. 12. It can be seen from Fig. 12 that the serious impact of jump and drift errors in adjacent correlation method can be overcome by the MLP correction method proposed in this paper.

In addition, in order to further understand the performance of the algorithm in this paper, the analysis and comparison of this method and the second compensation method in reference [10]. Based on the adjacent correlation correction method, the method in reference [10] compensates the micro-motion targets twice according to their periodicity and sinusoidal characteristics, and eliminates the impact of jump error and drift error. Comparison of the section curves of the IRT results through the second compensation method and the MLP correction is shown in Fig. 13. On the one hand, it can be clearly seen that the peaks after IRT corresponding MLP method have lower side lobes, which is mainly benefited from the more appropriate strategy for reference pulse selection. In other words, the method based on MLP was obviously better than the method based on second compensation method in terms of envelope correction performance. On the other hand, the method based on second compensation cannot be processed in real time because it depends on the global characteristics of the HRRP. However, for MLP-based correction method, each prediction is only related to several pulses before the current pulse, so this method has great potential for real-time processing.

Despite these advantages, the proposed algorithm based on MLP has its drawbacks. For example, because the network needs to be trained in each prediction process, the computational complexity of this algorithm is relatively large. However, with the continuous improvement of the current computing level, it can be accelerated by GPU or parallel computing and other means. Therefore, this algorithm has great potential in real-time and high-precision envelope correction of micro-motion targets in the future.

IV. CONCLUSION

For parameter estimation and imaging of micro-motion targets in the terahertz ISAR sensing, an envelope correction method based on multi-layer perceptron is proposed in this paper. Comparing to traditional envelope correction methods that are constrained to small-angle model, our method demonstrates its superiority in adjusting the range profile sequence and make it sinusoidal over time. Its key is to adjust the reference profile according to the correlation in time. In other words, if the correlation coefficient between the current profile and MLP output is larger than that between the current profile and the previous one, choose the MLP output of the several previous profiles as the reference profile. Conversely, the reference profile should be the profile prior to the current one. The validity of the method was verified by two experiments on micro-motion targets with a terahertz radar system, and its performance was measured and compared by the IRT results of the HRRP sequences. Finally, we analyzed some shortcomings of the algorithm and its solutions, and looked forward to its future applications.

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