The GPU implementation of micro-Doppler period estimation

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Abstract. Aiming at the problem that the computational complexity and the deficiency of real-time of the wideband radar echo signal, a program is designed to improve the performance of real-time extraction of micro-motion feature in this paper based on the CPU-GPU heterogeneous parallel structure. Firstly, we discuss the principle of the micro-Doppler effect generated by the rolling of the scattering points on the orbiting satellite, analyses how to use Kalman filter to compensate the translational motion of tumbling satellite and how to use the joint time-frequency analysis and inverse Radon transform to extract the micro-motion features from the echo after compensation. Secondly, the advantages of GPU in terms of real-time processing and the working principle of CPU-GPU heterogeneous parallelism are analysed, and a program flow based on GPU to extract the micro-motion feature from the radar echo signal of rolling satellite is designed. At the end of the article the results of extraction are given to verify the correctness of the program and algorithm.

1. Introduction

In recent years, the "micro-Doppler" effect of radar target has been used as the hotspot in the study of target feature extraction and identification [1]. [2-3] analyzes the micro-motion characteristics of the trajectory target and the sea surface rigid target respectively. The United States Navy Research Laboratory Chen has studied systematically on the target acceleration, rotation, vibration, tumbling state under the micro-Doppler shift [4], in addition, there are a lot of different designs of micro-motion feature extraction algorithm for different targets [5-7]. However, with the increasing of the radar bandwidth, the computational complexity of extracting the micro-motion feature from the radar echo is also increasing exponentially, which limits the real-time application of the micro-Doppler effect under the condition of wideband signal.

With the development of computer hardware technology, the Graphic Processing Unit (GPU) for general parallel computing has been greatly improved in terms of computing speed relative to the traditional CPU, and its architecture applies to high operational density signal processing algorithms. Although the CPU has worse computing performance than GPU in dealing with large-scale data, the modern CPU has highly efficient long instruction set structure, higher frequency and branch prediction. Therefore, CPU performs better in the coarse-grained thread management. GPU-CPU heterogeneous system is designed to give full play to the advantages of CPU and GPU, making the CPU and GPU work together. In a GPU-CPU heterogeneous system, the CPU is used to handle serial tasks and logic controls, and the GPU is used for parallel computing [8]. In this paper, the characteristics of micro-Doppler feature extraction algorithm and the features of CPU-GPU heterogeneous parallel hardware are combined to design the program flow for the micro-feature extraction.
In addition, the extraction algorithm requires a high accuracy of translational compensation. However, for the high-speed moving target, because of the existence of systematic error and random measurement error, it is difficult to directly apply the single radar measurement value to compensate for the target translation, which includes velocity, acceleration and high-order acceleration terms. The uncompensated error term will destroy the structure of the target micro-Doppler spectrum and most of the micro-feature extraction algorithm will fail. Gao Hongwei [9] analyzed the influence of velocity and acceleration on micro-Doppler earlier, and proposed a central method for velocity compensation, but the method does not apply to multi-component, and does not consider the speed of multi-order change rate. The rest are mostly based on the trajectory target model to study the translational compensation algorithm [10-12]. Based on the rolling satellite motion model and the radar observation environment, we will use Kalman filter combined with the target radar distance measurement to estimate the distance and velocity of the target in order to obtain more accurate target translational compensation information.

2. Micro-motion Model and feature extraction method

In this section, we analyze the theory of the micro-motion model and the algorithm used in micro-motion feature extraction, and describe the design idea of the algorithm according to the characteristics of the algorithm, provide the theoretical basis for the program flow design in the next section.

a. Micro-Doppler Mathematical Model of Rotating Target scattering points

Assuming that the phase and distance change caused by translational motion has been completed compensated, the radar and the rotating target center of mass are relatively stationary. The space fixed coordinate system (X, Y, Z) is created with the radar position as the origin O and the target is set to rotate around the X, Y, Z axis of the reference coordinate system with angular velocity \( \omega = (\omega_x, \omega_y, \omega_z)^T \). It can be seen from the derivation of [13] that the micro-Doppler frequency \( f_d \) of the scattering point on the rotating target can be expressed as:

\[
f_d = -\frac{2f_\Omega c}{c}[\hat{\omega} \cdot \sin \Omega t + \cos \Omega t \cdot \hat{r}_0] \cdot \hat{n}
\]  

(1)

Where \( f_c \) is the carrier frequency of the radar, \( c \) is the speed of light, \( \hat{\omega} \) is the oblique symmetric matrix of the unit rotation vector, \( r_0 \) is the vector of the target rotation center to the scattering point, \( \hat{n} \) is the unit vector of the radar to the target center of mass.

It can be seen from the above equation that the term containing time \( t \) has only \( \sin \Omega t \) and \( \cos \Omega t \), so the micro-Doppler frequency change is a sinusoidal curve with a period of \( 2\pi / \Omega \).

b. Joint time-frequency analysis

The time-frequency analysis method can estimate the instantaneous frequency on the basis of the time-frequency map, has become the most commonly used method in the current micro-Doppler effect study [14]. Joint time-frequency analysis includes Wigner-Ville distribution (WVD), short-time Fourier transform (STFT), continuous wavelet transform, S-transform and so on. Where STFT uses the spectrum to indicate the details of the change in the signal in time-frequency domain, which make it easy to use inverse Radon transform to extract the micro-motion feature. Therefore, we use STFT to carry on the time-frequency analysis to the signal.

STFT implements a Fourier transform on a short time window with the following expression:

\[
STFT(\tau, f) = \int_{-\infty}^{+\infty} x(t)w(\tau - f) e^{-j2\pi ft} dt
\]  

(2)

Where \( \tau \) and \( f \) represent the time and frequency, respectively, and \( \tau \) represents the position of the window on the time axis.
This article uses the Hamming window for STFT. In the use of STFT analysis, we need to combine the actual target rotation period and radar signal transmission frequency PRF, adjust the length of the window and the number of steps to find a compromise between the time resolution and the frequency resolution.

c. Inverse Radon transform

The Radon transform represents a function of the projection value of the ray passing through the object along with the projection direction and the distance. Its expression is as follows [15]:

\[ g(\theta, R) = \iint f(x, y) \delta(x \cos \theta + y \sin \theta - R) \, dx \, dy \]  

Assuming that there is a nonzero value \( f(x_0, y_0) \) at \((x_0, y_0)\) on the x-y plane, it can be seen from equation (3) that sinusoidal curve satisfying \( R = x_0 \cos \theta + y_0 \sin \theta \) in the \( R - \theta \) plane has the value \( f(x_0, y_0) \). Thus a point on the x-y plane is mapped to a sinusoidal curve on the \( R - \theta \) plane, whereas the inverse Radon transform maps the sinusoidal curve on the \( R - \theta \) plane to a point on the x-y plane.

The inverse Radon transform expression is as follows [15]:

\[ f(x, y) = \int_0^\pi d\theta \int_{-\infty}^{\infty} \{ g(\theta, R) * h(R) \} \delta(x \cos \theta + y \sin \theta - R) \, dR \]  

Where \( h(R) \) is the filter function.

Therefore, the extraction of the periodicity of micro-Doppler frequency can be realized by using the mapping relationship between the sinusoidal curve and the point in the inverse Radon transform.

d. Target tracking and detection

Radar tracking filter is establishing the target trajectory based on the estimation and prediction of the extracted target information, where the Kalman filter algorithm occupies the dominant position [16]. Using the target position, velocity and acceleration as the target state vector to describe the change of the target state through the dynamic equation, and using the recursive calculation method, the state of the target can be easily estimated.

According to [16], we set the first observation value \( x_0 \) as the initial state of the system, define the initial value of the covariance matrix \( P_0 \) as a diagonal matrix. Since the rolling satellite studied in this paper has no problem with motorized mutations, we use the most representative Singer uniform acceleration model, set a small state noise \( Q \), and then establish a fixed \( R \) noise model based on the noise statistics characteristics of multiple measurements.

3. Design and Implementation of Micro-Motion Feature Extraction Program Based on CPU-GPU

In this paper, we use GPU-CPU heterogeneous parallel method to improve the radar signal processing speed. The first level of parallelism is the command-level parallelism on the CPU, which uses CPU operating system complex control logic and branch prediction. In order to make full use of the server 4 core CPU performance, the frame header information extraction, pulse compression, Kalman filter, translational motion compensation, joint time-frequency analysis, and inverse Radon search changes are divided into several CPU coarse-grained threads to implement in parallel. And the data used in each process is in a sequential dependency, that is, the next process uses the data from the last process, so we use the CPU multi-threaded classic producer-consumer model for scheduling management between threads [17].

The second level of parallelism is the parallelism of single instruction stream for multiple data streams on the GPU. The GPU operates together with a large number of simple stream processors to improve computing and data throughput. Each stream processor operates in a single instruction stream multithreading and can only execute the same program [18], so the GPU is suitable for computationally intensive but simple and repetitive computational tasks. In the micro-motion feature
extraction process, whether it is the pulse compression based on the FFT algorithm, the translational motion compensation needed to do the cyclic shift and multiply the phase factor, or the micro-motion feature extraction based on the inverse Radon transform, can be decomposed into a large number of small sub-problem, and the sub-problems are independent of each other and have the same nature. So the computation of the feature extraction process can be distributed to multiple GPU fine-grained multi-threaded processing. The program flow chart based on CPU-GPU to implement the micro-motion feature extraction is shown as below:

**Figure 1.** micro-motion feature extraction program flow chart

In the figure, threadx represents the coarse-grained thread label of the CPU, and GPUs represents the using of the x-numbered GPU board to compute. As the server used in this article has four NVIDIA GTX960 board as a hardware support, so the computing task is divided into four more equal parts.
3.1. Echo sequence processing module

a. Pulse compression

Since the pulse compression processing is large and requires much CPU logic control, it is divided into parity pulses for processing to balance the size of the tasks. The core processing algorithm of pulse compression FFT decomposes the long sequence DFT into multiple short sequence DFT, so it has the characteristics of divide-and-conquer. The echo sequence is processed by calling API functions in the CUFFT library on the CUDA platform based on GPU hardware. When the amount of computation is large, the GPU-based FFT algorithm achieves more than 58 times faster than the traditional serial CPU-based [19].

b. Translational motion compensation

Using the uniform acceleration target model as the prediction model and the radar measurement as the observed value for Kalman filter. According to the threshold value of the wave front, the sampling frequency, and the Kalman filter estimated distance value, the data can be compensated and the peak and phase of the pulse are aligned. Kalman filter process calculation is so small that calling GPU kernel function processing has no income, so we implement it in the CPU thread.

Taking into account the hardware structure of the GPU, 512 threads are enabled to do cyclic shift and phase compensation for each frame of data, each thread handles m / 512 points of the shift and multiplied by the phase compensation factor, m is the number of points per frame. The thread access mode is shown in the following figure:

![Figure 2. The thread access mode](image)

In this mode the adjacent thread will access the adjacent data in the memory, so as to meet the GPU global memory alignment access requirements [18], which can speed up the data read speed and improve operational efficiency.

3.2. Micro-motion feature extraction module

a. Joint time-frequency analysis

After the pulse compensation sequence is obtained, the number of micro-motion point is judged. For the case of single scattering point, the inverse Radon search transform can be directly used to extract micro-motion feature from pulse compression results, the micro-motion period can be estimated according to the distance variation period. For the case of multi-scatter points, we intercept the portion of the data containing the scattered point information, sum it to obtain a one-dimensional vector containing the phase information, and perform STFT on the one-dimensional vector to obtain the time-frequency analysis matrix.

b. Micro-motion feature extraction

The micro-motion feature extraction includes the estimation of the micro-motion period and the separation of the micro-motion scattering points. We use the inverse Radon search transform method for periodic estimation. From the formula (4) we can see that the value of each point on the x-y plane in the inverse Radon transform corresponds to the integral computation along a sinusoidal curve on the R-θ plane. Therefore, the inverse Radon function also has the characteristics of divide-and-conquer. A thread in the GPU is enabled to be responsible for the calculation of a point on the x-y plane. When the inverse Radon search transform is used to estimate the period, the inverse Radon function needs to be called multiple times.
Reverse Radon search transformation method implementation steps are as shown below:

Figure 3. Inverse Radon search transformation flow chart. After estimating the micro-motion period, we can perform the inverse Radon transform of the full sampling time on the time-frequency analysis matrix to obtain the micro-motion separation matrix according to the correlation of the micro-motion period of the micro-motion scatter points.

4. Results analysis

In this paper, a sampling rate of 1.6GHZ is used, the maximum signal bandwidth can be set to 400 μs, so each echo sequence has 640000 points in float type storage, each point of four bytes. When the pulse transmission frequency PRF is 50Hz, the processing speed of data need to up to 122M/s to achieve in real-time processing. The use of the GTX960 has 1280 separate computing stream processors, theoretically, its speed ratio up to 1280 times compared to the serial calculation. But because the processor can not maintain full load operation, CPU memory and GPU memory between the data I/O operation takes a lot of time, slow memory read speed, CPU processing time bottlenecks and other factors, the acceleration ratio is much lower. But because of the simple logic of the micro-motion feature extraction algorithm and the high computational density, a high speed ratio can be obtained and the system can meet the requirement of real-time extraction of the micro-motion feature. The imaging results of GPU processing are shown in the following figure:

Figure 4. Radar measurement compensation pulse compression result

Figure5. Kalman filter compensation pulse compression result
In this paper, we analyze the results of the program processing of the tumbling satellite radar echo with three micro-motion scattering points, and the number of echo sequences is 1200. Fig. 4 shows the image of the pulse echo sequence using the radar distance measurement for translational compensation. Fig. 5 shows the results using the Kalman filter distance estimation. The straight line in the figure represents the non-micro-motion body echo, and the remaining three sinusoidal curves represent the echo of the micro-motion scattering points. It can be seen that the radar measurement can not compensate the echo completely due to the existence of the error, and the echo after compensation has the phenomenon of beating before and after. In contrast, the distance transformation curve becomes smooth by using the Kalman filter distance estimation to compensate, so the effectiveness of the Kalman filter algorithm for tracking the high speed moving target is verified.

Fig. 6 and Fig. 7 show the results of time-frequency analysis in response to the echo sequences of Figs.4 and 5, respectively. It can be seen from Figure 7 that after the phase compensation, micro-Doppler frequency also showed a sinusoidal curve changes. From the comparison between Fig. 6 and Fig. 7, it can be seen that the phase information is more sensitive to noise, and if there is no exact distance for phase compensation, the micro-motion characteristic of time-frequency analysis result will be destroyed. The micro-motion extraction algorithm based on the inverse Radon transform to extract the sinusoidal periodicity will be seriously defocused, and the correct period and scatter point separation image can not be obtained.

In order to a better observation of the role of Kalman filter in phase compensation, a one-dimensional vector data containing the phase information is derived for simulation analysis. The following figures shows the FFT image of the one-dimensional vector that uses radar measurements and Kalman filter estimation for phase compensation, respectively.
Figure 8. Phase contrast image

We can see that the measurement noise is effectively suppressed by using the Kalman filter estimation for phase compensation. In the result of normalization, the first side-lobe is reduced from -35dB to -50dB, and the amount of jitter is also greatly reduced, so that better time-frequency analysis results can be obtained.

According to the correct period estimation, the micro-motion separation matrix is obtained by performing inverse Radon transform on the time-frequency analysis results in Fig. 7. The results are shown below:

Figure 9. Micro-motion separation image

It can be seen that the inverse Radon transform of the full sampling time separates the micro-motion scattering points when the micro-motion period estimation is correct, and relative position relation between the target body and the micro-motion scattering points is obtained. Through the real-time changes of the micro-motion separation image, the attitude of the target relative to the radar can be roughly observed. At this point, the results verify the correctness of the micro-motion feature extraction program.

5. Conclusion
In this paper, the characteristics of high computing speed and applicable to signal processing algorithms of GPU is used to improve the problem of real-time performance of micro-motion feature extraction algorithm for wideband signal. Based on the existing micro-motion feature extraction algorithm, a complete program flow for extracting the micro-motion feature from radar echo is designed and programmed based on CPU-GPU heterogeneous parallel structure to verify the validity of the Kalman filter applying in tracking the track target and the feasibility of real-time extraction of the satellite target micro-motion feature.
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