High-resolution miniature UAV SAR imaging based on GPU Architecture

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Abstract. High-resolution miniature unmanned aerial vehicle (UAV) synthetic aperture radar (SAR) imaging requires not only effective and high-precision imaging algorithms, but also an efficient processing platform with real-time capability. In this paper, a graphics processing unit (GPU) based parallel scheme is presented to solve those problems. The polar format algorithm (PFA) is accelerated by utilizing the principle of chirp scaling (PCS) to avoid the two-dimensional (2-D) interpolation. Moreover, an efficient 2-D autofocus processing scheme is applied to compensate for the serious motion error caused by air turbulence. The specific realization on GPU and the main optimization method are investigated. The GPU based scheme is now able to process 4096×8192 complex image in a single precision within 4.23 seconds. The experimental results validates the effectiveness and efficiency of the scheme.

1. Introduction

Synthetic Aperture Radar (SAR), as one of the most important technologies in remote sensing, has shown great value in many fields for its ability to achieve fine-resolution images of targets in all-day and all-weather conditions [1]. The traditional SAR systems are usually mounted on the platforms of airplanes or satellites. Unfortunately, the expensive cost and difficulty in operation have precluded their use in circumstances requiring immediate and frequent revisits. As an alternative, the miniature unmanned aerial vehicle (UAV) SAR attracts growing interest in recent years for its small size, light weight and low cost [2]. However, due to the aerodynamic configuration, the UAV flight trajectory is easily disturbed by the atmospheric turbulence. The uncompensated motion errors result in severe degradation of the final SAR imaging quality.

Owing to its ability of compensation for undesirable antenna motion, polar format algorithm (PFA) is one of the most commonly used algorithms for spotlight SAR image formation [3], [4]. In order to reduce the computation loads, PFA based on the principle of chirp scaling (PCS) is applied, which replaces the two-dimensional (2-D) interpolation with fast Fourier transforms (FFTs) and complex multiplications [5].

In the complex operation environment, the UAV is too flexible to fly with constant velocity along a straight line. Meanwhile, the UAV platform is usually equipped with lower accurate motion sensor limited by undesired cost and load. The severe motion errors of UAV introduce not only phase error but also residual range cell migration (RCM). Thus, 2-D autofocus techniques are necessary for the coarse focused image. However, it is difficult for conventional 2-D autofocus algorithms to accurately estimate the residual RCM. The relationship between phase errors and nonsystematic RCM under a
new quasi-polar-coordinate-based fast factorized back-projection (FFBP) algorithm framework is presented in [6]. However, in order to develop the 2-D autofocus with PFA, an effective 2-D autofocus approach has been proposed based on [7], in which the analytical structure of the 2-D phase error under PFA framework is derivated in detail.

The rapid development of graphics processing unit (GPU) provides an available technical mean for real-time digital signal processing. The large-scale threads, great extensibility and transportability make the GPU a reasonable choice for SAR data processing and analysis [8]. To the best of our knowledge, most papers have researched the imaging algorithms on GPU such as back projection algorithm (BPA) and range migration algorithm (RMA) [9][10]. However, a complete GPU based parallel scheme for high-resolution miniature UAV SAR containing autofocus algorithm has rarely been analyzed.

In this paper, a GPU based scheme of processing UAV SAR echo data using the improved PFA and 2-D autofocus algorithms is put forward and its parallelizability is deeply excavated. It took 4.23 seconds to process a data matrix of 4096×8192 while employing a GPU Tesla C2075. Accordingly, this proposed scheme can obtain the fine focusing image, meanwhile meeting the real-time requirement.

2. SAR image formation algorithms

2.1. PFA using chirp scaling
The PFA is very compatible with the motion compensation and autofocus algorithms, as a result, it’s fairly suitable for high-resolution SAR imaging, especially when those unstable miniature UAV is employed. In order to ease the speed requirement for the A/D converter and the size requirement for digital memory, the received echoes of miniature UAV SAR system are usually de-chirped with the returned analog signal with a replica of the transmitted waveform [11].

Figure 1 illustrates the corresponding range and azimuth processing chain of PFA using PCS, which has been derivated and explained in detail in [12]. The range scaling of the de-chirped signal is composed of range FFT, a scaling function, a linearly dispersive filter and a redefined inverse scaling function. In similarity, the azimuth scaling processing accomplishes azimuth sampling. Furthermore, a 2-D Fourier transform is used to generate the coarse focused image.

(a) Range scaling (b) Azimuth scaling

Figure 1. Range and azimuth processing chain.

2.2. Two-dimensional autofocus
For those UAV platforms, the phase error tends to be of high order because of its low flight speed. The multi-subaperture phase gradient autofocus (PGA-MD) algorithm is a robust tool for the phase error compensation [13]. To implement the PGA-MD properly, we take following steps: Firstly estimate subaperture phase error (SPE) with the complete procedure of PGA, then derive the unknown constant phase from the MD operation of the subaperture image, finally combine the SPE and acquire the full aperture phase error (APE).
Ref. [7] investigated the effect of polar reformatting on the uncompensated APE and residual RCM in detail. The analytical relationship between the 2-D phase error and the full aperture phase error can be expressed as:

\[
\varphi_{2D} = \frac{K_x}{K_y} \varphi_{1D} \left( \frac{K_{wc}}{K_y} \right)
\]

(1)

where \( \varphi_{1D} \) represents the azimuth phase error, which can be estimated by PGA-MD, \( \varphi_{2D} \) is the 2-D phase error, \( K_x \), \( K_y \) denotes the azimuth and range wavenumber signal, respectively. \( K_{wc} = K_y (N_r/2) \), where \( N_r \) denote the range sampling number. This approach can make sure the residual RCM can be directly computed accurately instead of additional estimation procedures.

Based on the PGA-MD and the 2-D autofocus, an autofocus approach for miniature UAV SAR imaging is given in this paper. On one hand, the approach first estimate the full aperture phase error by means of PGA-MD. On the other hand, the 2-D autofocus is applied to complete residual RCM and space-variant phase error correction. The flow of autofocus is as Figure 2.

![Figure 2. Flow diagram of 2-D autofocus Algorithm.](image)

3. SAR processing based on GPU

3.1. Parallelization of PFA on GPU
The main processing step of PFA based on PCS consists of range scaling, azimuth scaling, FFT and IFFT, where the FFT and IFFT can be easily parallelized by using the CUFFT library. A central data-parallel kernel function is used to process chunks of data for the other operations. On the basis of parallel processing of kernel function, the CUDA stream is employed to achieving higher data processing efficiency. Stream is an asynchronous parallel mechanism, which allows data processing in kernels and data transmission between CPU and GPU concurrently [14]. Figure 3 illustrates the flow chart of stream asynchronous processing. First create a number of streams, then radar data is allocated to each stream averagely. The total time of kernel execution is constant, but the time of streaming data transmission is saved.

![Figure 3. Flow chart of stream asynchronous processing.](image)
The flow chart of PFA based on GPU is illustrated in Figure 4. Since the raw echo is transferred from host memory to GPU pulse by pulse and the streaming technique is employed, a transpose kernel is needed between the range and azimuth processing. And the coalesced memory accesses of shared memory is applied to accelerate the transpose operation.

3.2. Parallelization of 2-D autofocus on GPU
Compared to PFA, the parallelization of 2-D autofocus algorithm on GPU is more complex. The main optimization methods are listed as follows:

1) PGA makes a robust estimation of the phase error based on the defocus condition of strong scattering point. As a result, we select a number of range lines with maximum energy for APE estimation. It can greatly reduce the computation loads during the iteration phase correction. Therefore, a sorting algorithm is adopted to determine the iterative matrix after the strongest scatter for each range bin is selected.

2) In order to find the maximum among the data of \( N \) elements, the number of comparisons reaches \( N-1 \) when using the serial enumeration algorithm. As an alternative, the parallel reduction algorithm is adopted to find the strongest scatter in each range bin. It can greatly reduce the time complexity and improve the efficiency.

3) Accumulating the processed data along the range bin is an important step for phase gradient estimate. Atomic function in CUDA demands that only one single data can be added at the same time. This approach ensures the processing reliability by sacrificing performance, which is undesirable for parallel computing. Based on the matrix multiplication function \textit{cublasSgemm} provided by CUBLAS library, this paper proposes an improved method which accomplishes accumulation operation by multiplying the data matrix with a vector whose elements are all ones.

4) The purpose of the whole iteration is to calculate the azimuth phase error gradient. Skipping the final iteration, the subsequent operations can be performed as the phase error gradient have been obtained.
The complete flow chart of 2-D autofocus algorithm based on GPU is shown in Figure 5. The operations of data sorting and integration are accomplished on the CPU due to their poor parallel performance and light computation load. The value of reps is usually set as 6–8, ensuring the accuracy and effectiveness of 2-D autofocus algorithm.

4. Experimental results
Having discussed the parallelization of the PFA and 2-D autofocus algorithm, we present some empirical results. A six-core Intel(R) Xeon(R) CPU of 3.2 GHz with 32 GB random access memory was used. Parallelization was done using a GPU Tesla C2075 of 1.15 GHz, 2.0 capability, 6 GB global memory and 448 cores. And the version number of CUDA toolkit and SDK is 5.5. MATLAB and Microsoft Visual Studio 2010 are used for CPU and GPU programming, respectively. The experimental data was collected by an X-band miniature UAV SAR designed by Nanjing University of Aeronautics and Astronautics as shown in Figure 6. The eight-rotor mini-UAV is used to carry the SAR, and can fly for 30 minutes. The de-chirped signals are recorded by a sampling frequency of 50MHz. The detailed parameters of the mini-SAR are shown as Table 1.

(a)                                             (b)                                            (c)

**Figure 6. Structure of UAV SAR.**

![Figure 6. Structure of UAV SAR.](image)

| Systemic Parameters | Real Data |
|---------------------|-----------|
| Carried frequency   | 9.7GHz    |
| Bandwidth of signal | 1800MHz   |
| Pulse width         | 4ms       |
| Pulse repeat frequency | 250Hz    |
| Forward velocity    | 7m/s      |
| Height              | 480m      |
| Reference range     | 2056m     |
| Full synthetic aperture length | 300m |
| Full azimuth resolution | 0.1m |
| Range resolution    | 0.083m    |

**Table 1. System parameters of real data.**

![Table 1. System parameters of real data.](image)

(a) Image directly produced using GPU (b) Image refocused by 2-D autofocus using GPU (c) Image refocused by 2-D autofocus using CPU

**Figure 7. Experimental results of real data.**

![Figure 7. Experimental results of real data.](image)
The size of the raw data is 4096×8192, and the processing results of GPU and GPU are illustrated in Figure 7. The SAR image directly produced by PFA suffers from severe defocus as shown in Figure 7(a). The image is well-refocused after employing the 2-D autofocus algorithm as shown in Figure 7(b) (c). Meanwhile, the imaging results achieved by GPU and GPU are similar and both high-quality. In addition, we made a comparison between phase error estimated by GPU and CPU, as depicted in Figure 8. The phase error difference keeps within ±0.002 rad, which has little effect on the quality of the image. This experiment verifies that the accuracy of floating-point computation on GPU is high enough.

The image results on CPU and GPU are quite similar, while the running speeds are extremely different. To verify the acceleration and imaging efficiency on GPU, the spent time of PFA and 2-D autofocus based on CPU and GPU is compared. The results are presented in Table 2, the processing time in table does not include the time of data transmission between hard disk and memory. The speed-up radio of 2-D autofocus algorithm is far below PFA because of the complexity and its limitation of parallelization. In summary, the GPU based parallel scheme is over 43 times faster than the same processing procedure on CPU. The ideal acceleration ratio and real-time processing efficiency have been obtained.

In addition, the performance of the proposed parallel scheme can be described by the utilization of CPU and GPU. As shown in Figure 9, the resource utilization rate of CPU and GPU is very high, which greatly impact its efficiency.

5. Conclusions
In this paper, a GPU based parallel scheme for high-resolution miniature UAV SAR is proposed. In order to make the scheme more efficient and precision, PFA based on interpolation is replaced by a new implementation using chirp scaling. And the scheme makes full use of 2-D autofocus approach to improve the quality of motion error compensation. What’s more, the main optimization methods are described to improve the parallelization of scheme. According to the experiment results, it took about...
4.23 seconds to process a 4096×8192 complex-image in single precision. Meanwhile, the solution is efficient at making use of the computational resources. With the processing results of measured data of UAV SAR, the effectiveness and real-time imaging capability of the scheme are fully proved.

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