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A reconfigurable point target detection system based on morphological clutter elimination

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ABSTRACT

The point target detection application is widely applied to the field of medicine, military, and astronautics. To support good detectability of point targets and high-performance computing, this work proposes a point target detection system (PTDS) and a reconfigurable point target detection system (RePTDS). In the PTDS and the RePTDS, we propose a pipelined morphological clutter elimination (PMCE) hardware design that supports the point target detection application. Further, we also propose a hardware/software interface component that provides seamless data transfers between the PMCE hardware design and the microprocessor. To reduce the effects of the noise in the source images, different median filter functions are also designed in the PTDS and the RePTDS individually. Both the PTDS and the RePTDS can dynamically adapt their median filter functions to reduce the noise of the source images. Besides providing good detectability of point targets, according to our experiments, the PTDS and the RePTDS have been demonstrated that they can accelerate up to 165 times the processing time required by using the conventional point target detection method. Further, compared to the PTDS, our experiments have also demonstrated the RePTDS can provide more complete support of system adaptability for hardware functions, performance, and power consumption.

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1. Introduction

Target detection is a very important image processing application in the field of medicine, military, and astronautics. When infrared or visual image sequences are embedded with heavy clutters, target detection becomes very difficult. Thus, clutter elimination is very crucial, especially when the target is far away and appears as only a point. Nevertheless, the extraction of point targets from image signals is a complex task. Some filter-based methods, such as max-mean filer [4], max-median filter [4], multi-level filter [16], wavelet-based method [1], rectification filter [26], 2D adaptive lattice algorithm [7], and kernel smoothing methods [15], have been proposed to reduce the clutters of the images. However, when the source images are embedded with heavy clutters, the max-mean filer [4], the max-median filter [4], the multi-level filter [16], the wavelet-based method [1], and the rectification filter [26] cannot work efficiently. Moreover, although the 2D adaptive lattice algorithm [7] can reduce the clutters efficiently, the algorithm is too complex and time-consuming, so that it is not applicable to real-time systems. Compared to the 2D adaptive lattice algorithm, the kernel smoothing methods [15] are simpler. However, different mathematical assumptions of the clutter result in varying performance results, as a result of which the kernel smoothing methods are difficultly applied to the situations with undetermined mathematical model of the clutter. Therefore, an efficient and practicable clutter elimination method is necessary.

Due to parallel computing and ease of implementation in hardware, the morphology-based methods [9,25,27] were further proposed to decrease the effects of the clutter. However, the above methods [9,25,27] focused on the combination of the existing morphological operations, without the support of powerful clutter elimination. Based on contour structuring elements, the mathematical morphological methods, such as CB morphology [19], was proposed to maintain the images efficiently while filtering the clutter. However, CB morphological operations are still sensitive to heavy noise and clutter, thus degrading the detectability of point targets. By improving the CB morphology, another method using adaptive morphological clutter elimination (AMCE) [2] was proposed to enhance the detectability of point targets embedded with heavy clutter in infrared images. The AMCE method imported the properties of the point target regions, as a result of which not only the adaptive ability of the algorithm but its performance could be enhanced and improved significantly.

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Further, the dim small target could be apparently enhanced for applying to the forward-looking infrared system or the infrared guidance system. However, the hardware architectural features are not considered in the AMCE method. As a result, when the AMCE method is directly realized in hardware, the parallelism and performance are thus restricted.

By considering the ability of mathematical manipulation, most research works [6,13,17] adopt the DSP devices to implement the target detection applications. However, due to the limitation of sequential execution, the performance of point target detection application thus depends on the performance of the microprocessor. Recently, because of the ability of parallel computing and flexibility, reconfigurable logics such as the FPGA devices have also been applied to target detection applications [14,18] for supporting real-time requirements. Through the architectural feature, the operations of a target detection application can be processed in parallel, and thus system performance can be further enhanced [5]. To be able to not only meet hard real-time requirements but also support good detectability of point targets, an efficient and complete system design is thus required.

To solve the above problem, our previous work [10] has proposed a *Pipelined Morphological Clutter Elimination* (PMCE) hardware design that supports the point target detection application. Based on the previous work [10], this work further covers two issues to enhance system applicability, including (1) noise reduction: the noises of source images need to be reduced for enhancing the detectability of point target. (2) hardware adaptability: hardware functionalities need to be adapted on-demand to different requirements. As a result, we further propose an FPGA-based *Point Target Detection System* (PTDS) and a *Reconfigurable Point Target Detection System* (RePTDS). This work contributes to the state-of-the-art in the following ways.

- To support good detectability of point targets and to meet real-time requirements, this work refines the AMCE algorithm to support the FPGA implementation. A PMCE hardware design that integrates a parallel bubble sort method along with the buffering scheme is thus proposed. Compared to the conventional software solution, using the PMCE, system performance can be enhanced significantly. Furthermore, based on the parallel bubble sort method used in the PMCE design, a one-dimensional (1D) median filter and a two-dimensional (2D) one are also designed in the PTDS and the RePTDS to reduce the effects of noise in the source images. Thus, detectability of point target and system performance can be further enhanced. The PMCE design and the median filter design will be discussed in detail in Sections 2 and 3.
- To provide the seamless data transfers between hardware and software, a hardware/software interface component that contains software accessible registers, an interrupt controller and a bidirectional buffer is proposed in the PTDS and RePTDS. Through the interrupt controller, the microprocessor can be notified in real-time to receive data from the bidirectional buffer, when the data are ready. At the same time, the hardware module such as the PMCE can continuously write data to the bidirectional buffer. As a result, even though the frequencies of read and write operations are different, the data transfers between hardware and software can keep seamless. Details are given in Section 4.1.
- Different from the conventional point target detection system whose hardware adaptability is restricted, the proposed RePTDS can allow multiple tradeoffs and adapt to changing environment conditions at runtime. Through the self-adaptive mechanism, hardware functions in the RePTDS can be dynamically configured on-demand into the FPGA device, according to the environmental conditions. New hardware functions can also be configured in the FPGA, even though the total amount of required logic resources exceeds that available in the FPGA. This makes the utilization of hardware logics in the RePTDS more efficient. Furthermore, to meet low-power requirements, the RePTDS can dynamically configure the blank module in the FPGA device to reduce its power consumption. The RePTDS design and the related experiments will be discussed in Section 4.2 and Section 5, respectively.

This rest of this paper is organized as follows. Section 2 introduces the morphological clutter elimination method, while the PMCE hardware design is described in Section 3. The proposed PTDS and RePTDS are illustrated in Section 4. The experimental results and analyses are given in Section 5. Finally, conclusions are described in Section 6.

2. Morphological clutter elimination

Before introducing the PMCE hardware design, we first describe the background knowledge and the morphological clutter elimination method used in the PMCE design.

2.1. Preliminaries

This section will introduce the preliminaries of morphological clutter elimination method. Here, the input images used in this work will focus on gray-scale images.

Based on the classic mathematical morphology [8], the gray-scale dilation and erosion of the input image f by the structuring element b, denoted $f \oplus b$ and $f \ominus b$, respectively, are defined as in Eqs. (1) and (2).

$$f \oplus b(s,t) = max\{f(s-x,t-y) + b(x,y)\} \quad (1)$$

$$f \ominus b(s,t) = min\{f(s+x,t+y) + b(x,y)\} \quad (2)$$

where $(s \pm x), (t \pm y) \in D_f$ and $(x,y) \in D_b$. D_f and D_b are the domains of f and b, respectively.

The opening and closing of gray-scale image f by structuring element b, denoted $f \circ b$ and $f \bullet b$, respectively, are defined as in Eqs. (3) and (4).

$$f \circ b = (f \ominus b) \oplus b \quad (3)$$

$$f \bullet b = (f \oplus b) \ominus b \quad (4)$$

Based on CB morphology [19], b represents a planar structuring element, where ∂b represents the contour of b following the connectivity of b. The CB dilation, CB erosion, CB opening, and CB closing of f by ∂b are defined as in Eqs. (5)–(8), respectively.

$$CBD_b(f) = f \oplus \partial b \quad (5)$$

$$CBE_b(f) = f \ominus \partial b \quad (6)$$

$$CBO_b(f) = (f \ominus \partial b) \oplus \partial b \quad (7)$$

$$CBC_b(f) = (f \oplus \partial b) \ominus \partial b \quad (8)$$

Based on CB morphology, two operations, including $O_b(f)$ and $C_b(f)$, are further defined as in Equations in (9) and (10), respectively. Here, O_b and C_b can be used to estimate the clutter backgrounds of bright point target image and dark one, respectively.

$$O_b(f) = max\{f, CBO_b(f)\} \quad (9)$$

$$C_b(f) = min\{f, CBC_b(f)\} \quad (10)$$

The CB morphological clutter elimination f_T can be defined as in Eqs. (11) and (12). Here, f_b represents the estimated clutter background using C_b and O_b.

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