Energy Efficient Edge Detector Design for Ultra-low Power Image Processing

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Abstract— **The image/video applications in the portable devices such as smart phones have increased exponentially in recent years. This results in exponential rise in the design complexity of these devices. Moreover the advancement in the VLSI technology with nano-scale transistors dimensions results in further increase in complexity of these devices. The highly complex devices consume significant amount of energy while processing the signal. As the power/energy is the prime concern for the portable devices, highly energy efficient architectures/circuits are required to be developed. In several image processing applications edge detection is the commonly used operation to extract edge information available in the image. This information is further used to evaluate other parameters very efficiently. This paper a novel energy efficient edge detector is proposed, implemented and evaluated. The simulation results show that the proposed edge detector reduces area by 63.5% and delay by 31.8% over the existing well-known architecture.**

Keywords— **Digital Signal Processing (DSP), Edge Detector, Image Processing, Integrated Circuits, VLSI, Low Power Design.**

I. INTRODUCTION

The modern portable devices are getting more complex due to increased functionally on the save device to satisfy users demand. In order to support large number of functions on the same chip, the number of transistors that has to be fabricated on the chip is huge. With the continuous scaling of CMOS technology, billions of transistors can be fabricated on the same chip to implement the functionality. All the circuits on these portable devices demand highly energy efficient designs as user cannot manage with rapid discharge of battery [1]. The energy efficient designs not only increase the battery lifetime but also increases the reliability of the system. Further, these designs also reduce the cost associated with cooling the chip. Thus, in all the portable device energy efficient designs are required.

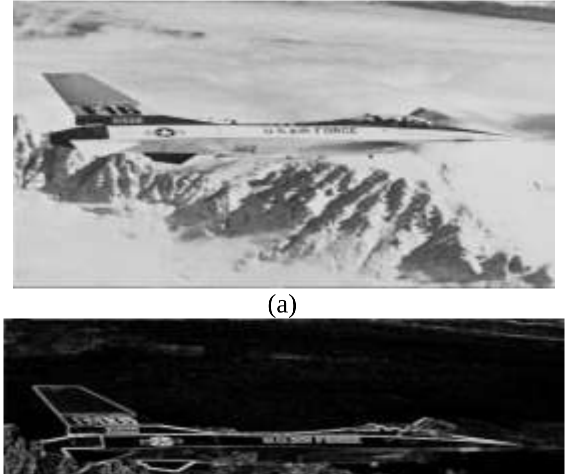
The primary design parameters (area, power and delay) form a tradeoff triangle i.e. improving one parameter damages the other. The conventional approach of VLSI design provides accurate results i.e. follow the given specification. But in real scenario it is not always required. There are many applications where minor error can be tolerated called as error tolerant applications. The multimedia applications such as image/video processing are error tolerant applications. In these applications, small error is tolerable as these applications produce output for human consumption [2] as human have limited visual perception. Along with the multimedia applications, several other applications such as that exhibit probabilistic computations and iterative computation also exhibits error tolerance. Thus, the accurate designs for these applications are the waste of power/area and performance. For these applications, accuracy can be seen as the new design parameter that can be traded to improve all design parameters.

In several image processing, machine, computer vision and feature extraction applications, edge detection is commonly used operation. The performance of the applications depends on the performance of the edge detector. Several existing edge detection [3]-[9] operators such as Canny, Sobel, Kayyali etc. existing in the literature are not efficient. This demands an energy efficient edge detector.

This paper proposes a novel edge detector that can be effectively utilized in the image processing applications. The designs are then evaluated using design and error metrics and compared with the well-known existing architectures. The simulation results shows that proposed edge-detector provides significantly improved design metrics and simultaneously provides acceptable quality.

II. EDGE DETECTION ALGORITHM AND ARCHITECTURE

Image processing exhibits different processing to enhance the desired feature while hides/reduces the undesired one. Various processing may include zooming, shape detection of an object, gray scale conversion. Edge detection has wide applications in the automatic industry to medical imaging. The edge of airplane image is shown in Fig. 1.



(a)

(b)

Fig. 1: Illustration of a) Original image, b) Edge of the image.

There are several techniques [10]-[15] in the literature that are used to find the edge including Canny, Kayyali, Robert, Laplacian of Gaussian and Sobel etc. Sobel, Prewitt and FreiChen are 3x3 masks operators. Although the Prewitt kernels is computationally simple over the Sobel, but the Sobel operator provides superior noise suppression over the Prewitt. Further, the complexity of the LOG is larger than previous mentioned operators.

2.1 Robert's Cross Operator:

The simplest and the computationally efficient operator is Robert's Cross operator which computes 2-D spatial gradient of an image. The pixel values at each coordinate represent the gradient in spatial domain. The operators are very simple and compute the gradient in the diagonal direction. The two operators (G_x and G_y) are orthogonal to each other and can be used to compute gradient separately. The two gradients can then be combined to achieve the overall gradient which reflects the edge of the image. The overall gradient and the orientation is given by the Eq. (1) and Eq. (2).

$$|G| = \sqrt{(G_X^2 + G_Y^2)} \qquad (1)$$

$$\theta = \tanh^{-1}\frac{G_X}{G_Y} - 3\frac{\pi}{4} \qquad (2)$$

The advantages of the Robert's operator is its simple architecture and low complexity of implementation but it shows poor noise immunity therefore, cannot be used in the highly noisy environment.

2.2 Sobel Operator:

The limitation of the Robert operator can be overcome by the Sobel operator whose pair of 3x3 kernels is shown in Figure 2 [1]. The Sobel operators computes maximum gradient in horizontal and vertical directions which are then combined to achieve overall gradient. Further one operator can be achieved by rotating 90^o the other.

$$G_x = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}; \qquad G_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$$

Figure 2: Kernel for the Sobel Edge detector

The gradient magnitude and its orientation is given by Eq. (3) and Eq. (4).

$$\theta = \tanh^{-1}\frac{G_X}{G_Y} \qquad (3)$$

Further, to reduce the complexity of the gradient magnitude can be computed using sum of absolute values which is given by Eq. (4).

$$|G| = |Gx| + |Gy| \qquad (4)$$

The advantage of the Sobel edge is its higher noise immunity i.e. it provide less sensitivity the noise and provides higher sensitivity to the edges. Therefore it the most commonly used operator used in the edge detector.

2.3 Prewitt Operator:

The Prewitt kernels also compute the gradients in horizontal and vertical directions and the resulting gradient is computed with the help of these two gradients. The operator has nearly same complexity as the Sobel but has little small noise immunity.

2.4 Laplacian of Gaussian Operator:

The Laplacian operator measures the second order gradients over the Sobel and Robert which compute gradient of first order. This Laplacian operator provides higher intensity over the region which have higher gradient i.e. large darker to brighter or brighter to darker change. The Laplacian operator with image I(x,y) is given by Eq. 5.

$$L(x,y) = \frac{\delta^2 I}{\delta x^2} + \frac{\delta^2 I}{\delta y^2} \qquad (5)$$

The most commonly used kernels that represent an approximation of the discrete Laplacian are shown in Fig. 3.

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & -4 & 1 \\ 0 & 1 & 0 \end{bmatrix}; \quad \begin{bmatrix} 1 & 1 & 1 \\ 1 & -8 & 1 \\ 1 & 1 & 1 \end{bmatrix}; \quad \begin{bmatrix} -1 & 2 & -1 \\ 2 & -4 & 2 \\ -1 & 2 & -1 \end{bmatrix}$$

Figure 3: Commonly used Laplacian kernels

The Laplacian of Gaussian provides the better performance in terms of noise immunity. It Guassian filter before Laplacian eliminates the impulse noise and provides higher value to the edges only. Most of the existing techniques suffer from the higher computational complexity and area inefficiency. The proposed filter given in the next section overcomes this limitation.

III.PRAPOSED WORK

This section presents the proposed novel algorithm for edge detection and its architecture.

3.1 Proposed Horizontal and Vertical Masks

In order to achieve energy efficient, we remove the unwanted pixels from the given data before finding the edges of the image. As we can see that there are 10 non-zero terms in the 5x5 Sobel operator for each gradient i.e. Gx and Gy, this will requires 17 adder to implement the whole Sobel edge detector. The hardware can be reduced significantly without much distortion in the output images by eliminating some of the non-zero terms. The proposed edge detector masks for Gx and Gy are given below:

$$Gx = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

$$Gy = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Here, the proposed algorithm first calculates horizontal gradient and vertical gradient by using of proposed horizontal (Gx) and vertical mask (Gy). Input image is applied and image is convert into number of 5x5 matrix, then it will convolved with Horizontal mask and generates the vector directional derivates, in same way the vertical mask is applied to generate vertical gradient.

The main assumption of masking is made by considering the concept of inter pixel correlation. The pixel values in an image are very close to each other and the variation is almost equal to one. Instead of processing the entire pixel in 5x5 kernels, a suitable mask is applied as a filter which passes horizontal and vertical pixels as shown in below Figure 4.

3.2 Proposed Diamond Mask:

The overall proposed edge-detector mask as given below is consists of few values which are to be processed that results in fast computation and low area and power consumption at architectural level. The new filter mask consists of negative and positive values. By applying absolute on the result values and summing up them generates the same conventional function with reduces complexity.

$$\begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

Figure 4: Mask kernel for Sobel operator

The value of horizontal and vertical gradients is evaluated based on the horizontal and vertical mask which is then used to compute final value of pixel of the edge image as given by the expression below.

$$G_{x1} = Absolute(G_x) \tag{13}$$

$$G_{y1} = Absolute(G_y) \tag{14}$$

$$Sobel\ Edge\ Pixel = G_{x1} + G_{x2} \tag{15}$$

3.3 Circuit diagram of the proposed edge detector:

The proposed edge detector as shown in Figure 5 below consists of only adders. The proposed edge-detector requires least hardware over the existing designs. The sizes of first two adders are 8-bit whereas for the last one is 9-bit. Due to the reduce hardware, the proposed design provides significant improvement in area, power and delay metrics.

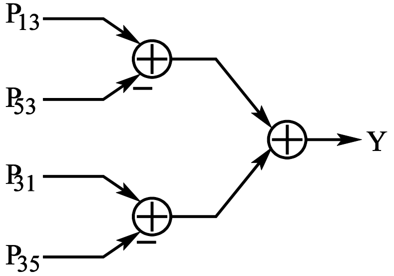


Figure 5: Proposed edge detector circuit diagram

Next section shows the efficacy of the proposed edge detector over the existing by implementing and simulating using EDA tools.

IV. EXPERIMENTAL RESULT & ANALYSIS

In order to evaluate the quality metrics [18], [19], MATLAB tool is to model the proposed and existing architectures of the edge detector. These implemented designs on MATLAB are then simulated with standard test images such as Lena, Baboon, and Plane etc. On the other hand, to evaluate the design metrics designs are implemented and Verilog HDL and simulated on ModelSim EDA tool. Further, the functionality of the proposed design is rigorously verified on ModelSim. Finally, the design is implemented on the Tanner 14.1 and simulated to extract design metrics such as area, power and delay.

4.1 Error Metrics:

The simulation results from MATLAB as shown in Table 1 are extracted by simulating design with the 1,000,000 random input patterns. It can be observed that the proposed design provides higher PSNR for AIRPLANE image over the BABOON's image.

Table I: Error metrics comparison

Metric	IMAGE	3X3 Accurate	3X3 Absolute	Proposed
PSNR (dB)	Baboon	13.87	12.35	14.15
	Barbara	14.67	12.05	17.98
	Airplane	17.57	15.72	21.56
SSIM	Baboon	0.6423	0.5871	0.6523
	Barbara	0.6987	0.5887	0.7054
	Airplane	0.6955	0.5401	0.7231
FSIM	Baboon	0.778	0.735	0.8509
	Barbara	0.8501	0.8142	0.8544
	Airplane	0.8093	0.7676	0.8623

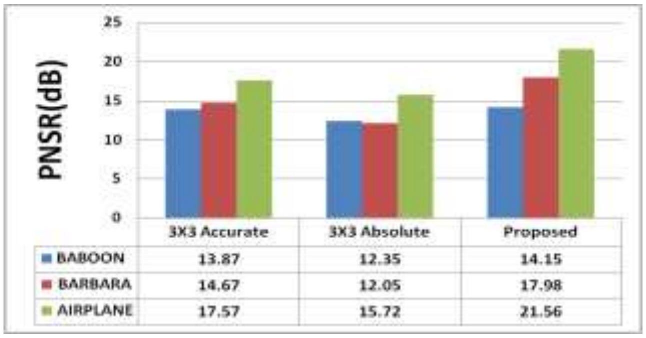


Figure 6: PSNR comparison for different ED

4.2 Architectural level analysis:

In order to evaluate the design metrics all the existing and the proposed edge-detector architectures are implemented in Verilog. These designs are simulated for functional verification. Further the designs are synthesized and are implemented in FPGA (Spartan 6). The simulation results as summarized in Table 2 shows that proposed design requires very less area over the existing accurate design. The number of logic block required in the proposed design is only 46 as compared to the 126 in the accurate design. Further it can also be observe that proposed design significantly reduces delay and time/frame.

Table 2: Comparative result of FPGA

Parameter	3X3 Absolute	Proposed
Logic Block	126	46
Delay (n Sec)	5.061	3.456
Frequency (MHz)	196.98	289.35
Time/frame (µSec)	518.24	127.4

The comparison of different design metrics as shown in Figure 7 and Figure 8 reveals that proposed design requires less logic block, less delay and higher frequency.

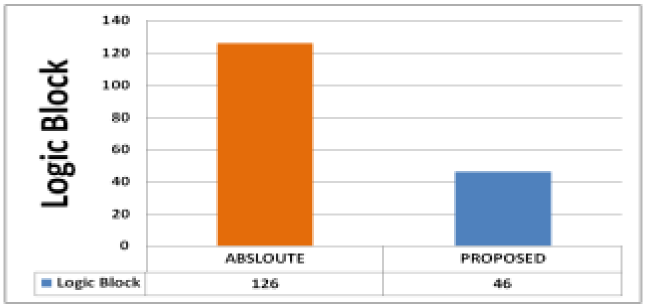


Figure 7: **Comparative analysis of logic block**

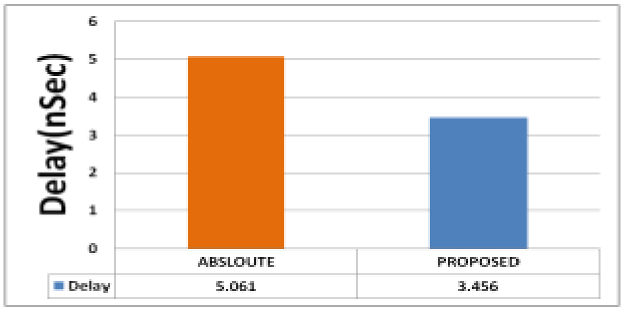


Figure 8: Comparative analysis of delay

(a) Standard Sobel Edge Detection

(b) 3X3 Accurate Sobel Edge Detection

(c) 3X3 Absolute Sobel Edge Detection

(d) 5X5 Proposed Sobel Edge Detection

Figure 9: Edge images using various edge detectors

V. CONCLUSION

This paper presents a novel 2D Gaussian smoothing filter that provides tremendous improvement in power, delay and area with small loss in accuracy. The novel 2D Gaussian smoothing filter provides high the speed by the approximating the kernel coefficient. Comparisons with conventional Gaussian smoothing filters showed that the proposed novel 2D Gaussian smoothing filter performed better than the all conventional Gaussian smoothing filters in both power consumption and speed performance. Novel 2D Gaussian smoothing filter can be utilized in all those applications where there is no exact requirement of accuracy or where ultra low power and high-speed are more important than accuracy. The proposed design is best suited in low power battery operated devices such as mobile and other gadgets.

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