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# A Novel Quality Tunable Gaussian Filter Design

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***Abstract: The energy efficient designs are the prime requirement for the modern portable device. The multimedia applications on these devices exhibits error tolerant due to limited human perception. The different applications exhibit different error tolerance. Therefore, quality tunable designs that provides improved quality energy tradeoff is becoming a challenge to the VLSI designer. In this paper a novel quality tunable Gaussian filter is proposed that provide higher energy efficiency and can be operated in different quality energy tradeoff modes. The design is implemented, simulated and compared to the existing filter architectures. The simulation results show the proposed filter provides 7.5% improved performance over the best-known existing architecture.***
***Keywords:  Gaussian Filter, Image Processing, Integrated Circuits, VLSI, Low Power Design.***

## I. INTRODUCTION

The energy efficient designs are major challenge to the VLSI designer as the portable devices are operated with a limited power source, large power consumption causes rapid discharge of battery. Therefore, energy efficient design is challenging task and become severe for the portable device because it requires large battery size and requires costly cooling circuitry to maintain the temperature of the device. The modern portable devices frequently employ multimedia applications that produce output for human consumption. Due to the limited visual perception, human can accept errors. The filtering operation is the most frequently used operation as the noise in the present electronic devices can come from anywhere e.g. while transmission, storage etc. Most commonly employed filter in image processing is the smoothing filter [1]. Various architectures are developed by the research that efficiently filters the noisy image. The concept of coefficient approximation into power of two is presented such that resulting coefficients can be realized without any multiplication logic. Other approach utilizes the similarity existing in the neighbouring pixels. Further, some of the approaches utilizes approximate adders to achieve low complexity filter architecture. In contrast to various fixed accuracy architectures, architecture that can provide different quality energy trade-off is also presented. An energy scalable GSF architecture is proposed in that exploit relative significant of kernel coefficients.
the remainder of the paper is organized as follows. Section II provides related work on various Gaussian filters whereas Section III provides architecture of energy scalable GSF. Section IV present proposed reconfigurable GSF. Experimental analysis is given in Section V while conclusion is given in Section VI.

## II. APPROXIMATE GAUSSIAN FILTERS

The Gaussian filtering is frequently employed in different image processing applications such as edge detection to remove unwanted edge, image mosaicking and tone mapping [2], [3] etc., it requires two dimensional (2D) Gaussian expression due to the 2D nature of the image. The 2D Gaussian expression is given by Eq. 1.

$$g(x,y) = \varepsilon^{\frac{-(x^2+y^2)}{2\sigma^2}} \quad (1)$$

where, x and y are the variables representing the coordinate while sigma representing the standard deviation. The processing of image through the above expression requires implementation of above expression in the software form which performance inefficient. Therefore, efficient implementation is done for the GSF. From VLSI implementation of the above expression is area and performance efficient, therefore, it is approximated by a matrix called kernel. The image processed through the Gaussian kernel provides nearly same result as Eq. 1. The accurate representation of the Gaussian expression using Gaussian kernel of 5x5 size is given by Eq. (2).

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$$\begin{bmatrix} 0.0030 & 0.0133 & 0.0219 & 0.0133 & 0.0030 \\ 0.0133 & 0.596 & 0.0983 & 0.0996 & 0.0133 \\ 0.0219 & 0.0983 & 0.1621 & 0.0983 & 0.0219 \\ 0.0133 & 0.596 & 0.0983 & 0.0996 & 0.0133 \\ 0.0030 & 0.0133 & 0.0219 & 0.0133 & 0.0030 \end{bmatrix}$$

The value of the coefficient of this matrix are obtained by varying the value of variable from [-2,2]. From the Figure it can be seen that direct implementation requires floating point multiplier to achieve smoothened pixel, therefore different approximations are done to achieve kernel coefficient which are hardware efficient. Based on the approximated coefficients, different architectures are developed.

### A. Gaussian Kernel with Fixed-point Coefficients

A Gaussian coefficient with integer kernel coefficient is used to achieve approximate kernel [4]. In fixed point representation in (l, m) format, l represents the number of bits while m represents location of coefficient least significant bits. The Gaussian smoothing kernel rounded to the (2, -4) and (6, -8) data formats are given by Eq. (3) and Eq. (4). These kernels reduce implementation complexity of the Gaussian filter which results in significant reduction in power, area and delay metrics at the same time the proposed kernels provide the acceptable output quality.

$$\frac{1}{2^4}\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 2 & 1 & 0 \\ 0 & 2 & 3 & 2 & 0 \\ 0 & 1 & 2 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\frac{1}{2^8}\begin{bmatrix} 1 & 3 & 6 & 3 & 1 \\ 3 & 15 & 25 & 15 & 3 \\ 6 & 25 & 41 & 25 & 6 \\ 3 & 15 & 25 & 15 & 3 \\ 1 & 3 & 6 & 3 & 1 \end{bmatrix}$$

### B. Approximate 2D Gaussian Filter

An approximate kernel with coefficient in power of two is reported in [5] that significantly reduces the implementation complexity of the Gaussian kernel. In this approximate kernel each coefficient is approximated in sum of power-of-two. Since constant multiplication in the power of two does not require any hardware all the coefficients are approximate in the power of two form. The resulting Gaussian kernel with value in power-of-two is given by Eq. (5). To maintain the sum of coefficient to unity, a constant value is multiplied. A simplified architecture is developed that utilized the kernel coefficients in the power-of-two form and compute the smoothened pixel.

$$(2^{-3}+2^{-6}).\begin{bmatrix} 0 & 2^{-3} & 2^{-3}+2^{-4} & 2^{-3} & 0 \\ 2^{-3} & 2^{-2}+2^{-3} & 2^{-1}+2^{-3} & 2^{-2}+2^{-3} & 2^{-3} \\ 2^{-3}+2^{-4} & 2^{-1}+2^{-3} & 2^{0}+2^{-4} & 2^{-1}+2^{-3} & 2^{-3}+2^{-4} \\ 2^{-3} & 2^{-2}+2^{-3} & 2^{-1}+2^{-3} & 2^{-2}+2^{-3} & 2^{-3} \\ 0 & 2^{-3} & 2^{-3}+2^{-4} & 2^{-3} & 0 \end{bmatrix}$$

### C. Gaussian Filter Exploiting Neighbour Pixels Similarity

Since the neighbour pixels in an image exhibits higher correlation i.e. similarity, it can be exploited to reduce the implementation complexity [6]. The adjacent pixels exhibit higher correlation in an image. This higher correlation in the image is due to the fact that image have smoothened nature and the large difference will occur only on the edge. As the natural and most of the images have edge which is very small in number, it makes assumption of adjacent pixel to be nearly same true. In case of image smoothing, an image sub-matrix is considered for processing for example a 3x3 image sub-matrix. In this method, pixels of an image sub-matrix row are approximated to single value where the coefficient of each row can be added and multiplied with the resulting pixel, as it will provide nearly same value. It can be seen from the Fig. 1 that the filter requires only two adders as the shifter does not requires and hardware. Moreover, the divider does not require any hardware as its value in in the power of two which can be achieved by right shifting the bits.

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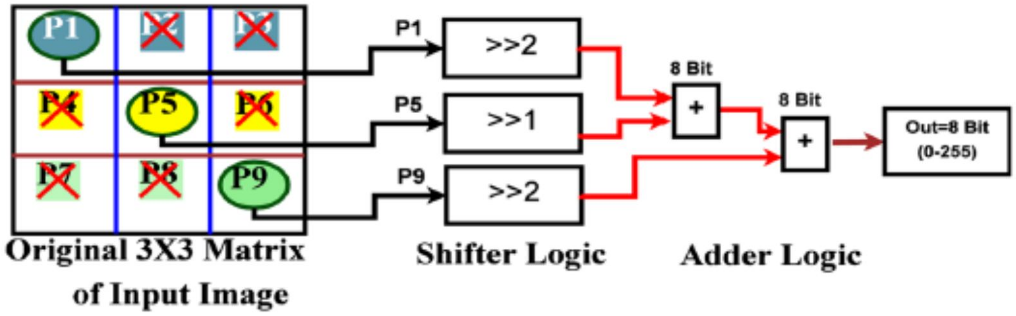


Fig. 1: Approximate filter using 3x3 window.

*D. Approximate Gaussian Filter using Approximate Adders*

An approximate Gaussian filter is proposed in [7] where approximate adders are embedded in the accurate GF architecture to reduce the area, power and delay. In the proposed approximate GF, different bit-width adders are explored to achieve power quality trade-off. The kernel coefficients to design approximate filter is shown in Fig. 2. These coefficients are achieved with sigma is equal to 1.4.

$$\begin{bmatrix} A1 & A2 & A3 & A4 & A5 \\ A6 & A7 & A8 & A9 & A10 \\ A11 & A12 & A13 & A14 & A15 \\ A16 & A17 & A18 & A19 & A20 \\ A21 & A22 & A23 & A24 & A25 \end{bmatrix} * 1/159 \begin{bmatrix} 2 & 4 & 5 & 4 & 2 \\ 4 & 9 & 12 & 9 & 4 \\ 5 & 12 & 15 & 12 & 5 \\ 4 & 9 & 12 & 9 & 4 \\ 2 & 4 & 5 & 4 & 2 \end{bmatrix}$$

Fig. 2: Gaussian kernel with sigma=1.4.

The approximate adders such as error tolerant adder are utilized to achieve energy efficiency. The architecture of the approximate 3x3 Gaussian filter is shown in Fig. 3. This architecture requires small number of adders which are further approximated to reduce the implementation complexity.

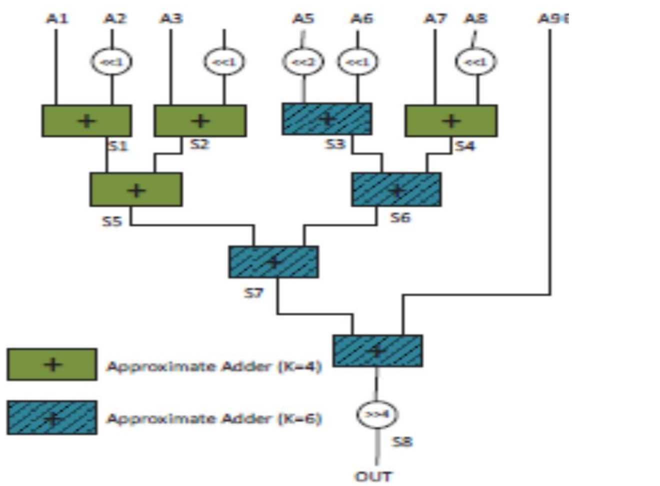


Fig. 3: 3x3 Gaussian filter architecture.

*E. Reconfigurable Gaussian Filter*

The Reconfigurable architecture is the prime requirement due to the ever changing real-time applications. Based on the applications and its criticalness, the design should be able to adapt different energy-quality trade-off which is achieve by the energy scalable GSF (ES-GSF) [8]. This architecture exploits the concept of significant/non-significant coefficients and presented significant and non-significant boundaries. It observed that value of coefficient decrease from centre to the boundaries therefore, boundary $B_1$ is more

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significant (due to having more weight) over the $B_4$. The ES-GSF exploits the non-significant boundaries to achieve desired quality energy trade-off. Further, the coefficient of the given boundary is of same value, the resulting architecture will compute sum of all pixel of that boundary and multiplied with the coefficient. The architecture that implement the functionality presented in the algorithm is shown in Fig. 4.

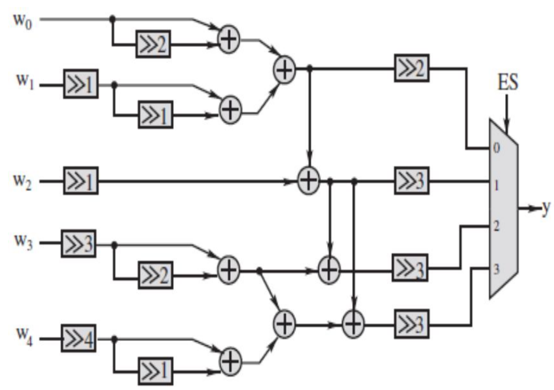

Fig. 4: ES-GSF Architecture.

It can be observed that ES-GSF provides trade-off between performance and quality. From the above mentioned architectures of the Gaussian filters, it can be observed that most of the architecture exhibits fixed accuracy designs and requires large redesign efforts to employ the in the application with different quality energy requirement. Only single architecture exists for quality tuneable Gaussian filter. Therefore, a quality tuneable design for Gaussian filter is required that provide higher energy efficiency with unnoticeable quality degradation. The next section present proposed quality tuneable Gaussian filter architectures.

## III. PROPOSED QUALITY TUNEABLE GF ARCHITECTURE

In order to reduce the implementation complexity of the Gaussian filter, the kernel coefficients are approximate from floating point to integer value. The resulting approximate kernel is given by Eq. (5). The coefficients of this kernel can be efficiently implemented using only few adders.

$$k_P = \frac{1}{160}\begin{bmatrix} 2 & 4 & 5 & 4 & 2 \\ 4 & 9 & 12 & 9 & 4 \\ 5 & 12 & 16 & 12 & 5 \\ 4 & 9 & 12 & 9 & 4 \\ 2 & 4 & 5 & 4 & 2 \end{bmatrix}$$

Further, to achieve quality tuneable design, number of non-significant coefficients are decimated. This decimation reduces the number of computation which will result in less energy consumption. Although the decimation of the coefficients reduces the quality of the output image, the effect is unnoticeable. The proposed decimated kernels are shown in Fig. 5.

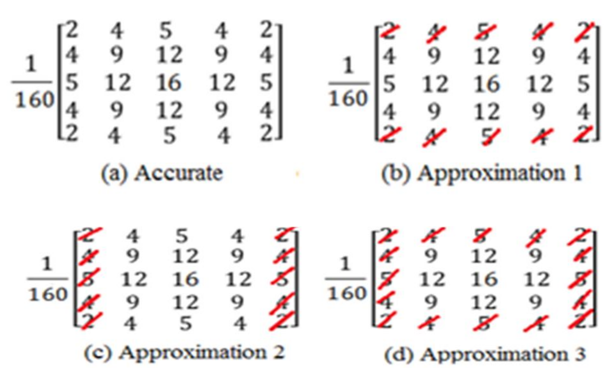

Fig. 5: Proposed approximate kernels.

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Therefore, in the proposed approximate kernels, either outer rows or column or both are eliminated. The resulting kernels are of 5x5, 3x5, 5x3, and 3x3 for accurate, approximate 1, approximate 2, and approximate 3, respectively. The accurate architecture requires large energy to achieve improved quality while the approximate 3 provides highest energy saving at the cost of small quality loss. In order to reduce the implementation complexity, the image pixels corresponding to different kernel coefficients which are decimated altogether are computed as shown in Fig. 6. These coefficients then considered for evaluating the Gaussian output using the control signal. The architecture that select appropriate kernel coefficients to evaluate the filtered pixel is shown in Fig. 7.

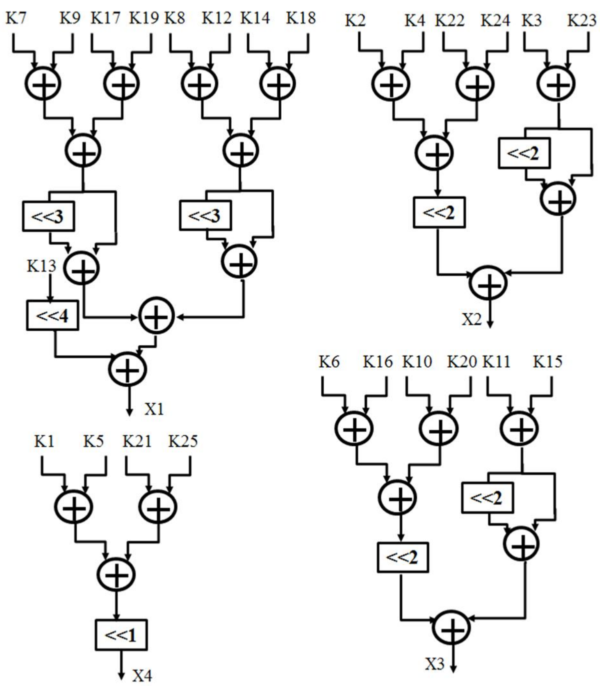

Fig. 6: Circuit diagram to compute common pixels computations

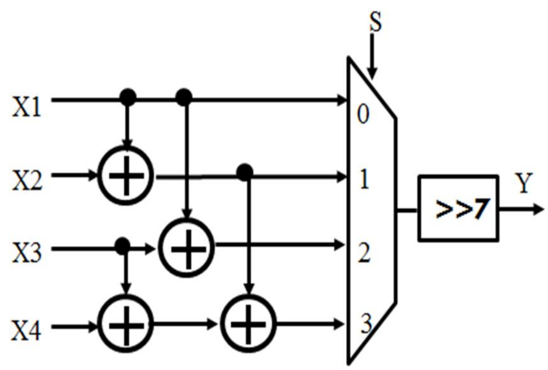

Fig. 7: Architecture of the proposed quality tuneable Gaussian filter.

The control signal S determines the number of kernel coefficients which are considered to evaluate the filtered pixels. The proposed architecture works in four modes: The filtered pixels are evaluated using Gaussian kernel as shown in Fig. 6(d) when the signal S = 00, whereas, the filtered pixels are evaluated using Gaussian kernel as shown in Fig. 6(c) when the signal S= 01, whereas, the filtered pixels are evaluated using Gaussian kernel as shown in Fig. 6(b) when the signal S= 10, whereas, the filtered pixels are evaluated using Gaussian kernel as shown in Fig. 6(a) when the signal S= 11.Further, in these different modes of operation, the proposed filter exhibits different delay metrics. This delay increase with increase in the number of kernel coefficients. The delay in different modes are:
Delay= 4TA+TM when S=00,
Delay= 5TA+TM when S=01,
Delay= 5TA+TM when S=10, and
4Delay= 6TA+TM when S=11,
thus, the proposed filter provides trade-off between quality and the performance. Further power gating the undesired coefficients significantly reduces the power consumption under approximation modes.

## IV. EXPERIMENTAL RESULT & ANALYSIS

The proposed filter is implemented evaluated over the existing architectures by implementing designs on MATLAB and Tanner computing the quality metrics and design metrics by simulating with benchmark images [9]. On the other hand, to evaluate the design metrics designs are implemented on Tanner schematic editor. Finally, the design metrics such as area, power and delay are extracted for the proposed and existing designs and compared.

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### *A. Quality and Design Metrics*

Various quality parameters are used to evaluate the design. The mean square error (MSE), mean error distance (MED) which is nothing but mean error, normalized error distance (NED) is equal to MED normalized to maximum value of signal. Besides this peak signal to noise ratio (PSNR), and structural similarity (SSIM) are also used as quality metrics [10], [11].

### *B. Quality results*

The quality metrics of the proposed and existing filter architectures are shown in Table 1.

TABLE 1: Quality metrics of various filters.

| Parameter | MED | MSE | NED | PSNR | SSIM |
|---|---|---|---|---|---|
| Acc_GSF | 13.032 | 272.13 | 0.1489 | 23.78 | 0.8707 |
| MA_GSF | 13.61 | 296.88 | 0.1487 | 23.4 | 0.857 |
| BG_GSF | 14.59 | 348.93 | 0.1327 | 22.7 | 0.781 |
| ESGSF | 18.2 | 270.78 | 0.168 | 23.8 | 0.8739 |
| LASCAS | 96.85 | 12557 | 96.85 | 7.14 | 0.0075 |
| QT_GF | 14.08 | 320.5 | 0.1638 | 23.07 | 0.8134 |

The comparison of the quality metrics PSNR and SSIM for different Gaussian filters are shown in Fig. 9 and Fig. 10, respectively. Higher the value of the PSNR and SSIM better the design. It can be observed from these figures that the LASCAS filter architecture presents worst case quality over the existing architectures. Further, the ES-GSF provides the best quality over the all the Gaussian filter architecturs.

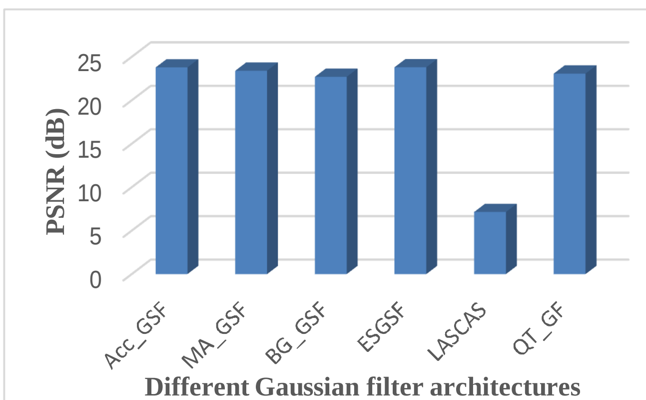



Fig. 8: PSNR for different GSF architectures.

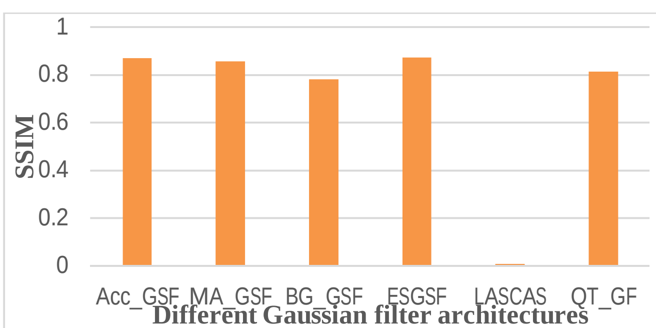
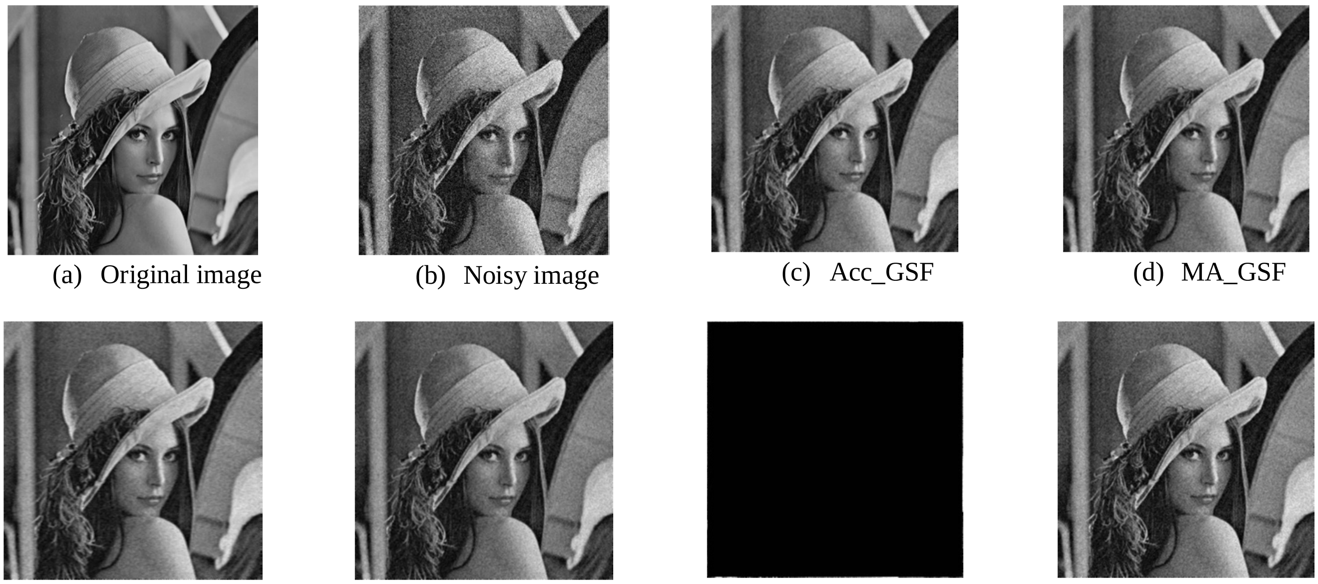



Fig. 9: Comparison of SSIM for different Gaussian filters.

Although, the proposed GSF architecture provides little small vaule of the PSNR and SSIM, this effect is unnoticable in the image quality as shown in Fig. 11. Therefore, the propsoed quality tuneable Gaussian filter can be efficiently employed in the modern portable devices exhibiting image processing applications.



(a) Original image (b) Noisy image (c) Acc_GSF (d) MA_GSF

(e) BG_GSF (f) ES-GSF (g) LASCAS (h) QT_GF

Fig. 10: Reconstructed images using various GSFs

Further, the proposed design is simulated under different quality modes and the corresponding simulation results are shown in Table 2.

TABLE 2: Quality under different modes.

| Parameter | MED | MSE | NED | PSNR | SSIM |
|---|---|---|---|---|---|
| ES-GSF1 | 18.22 | 528.1 | 0.193 | 20.9 | 0.8228 |
| ES-GSF2 | 21.7 | 745.3 | 0.2651 | 19.4 | 0.8128 |
| ES-GSF3 | 26.55 | 1091 | 0.3707 | 17.75 | 0.7943 |
| ES-GSF4 | 47.4 | 3210 | 1.0299 | 13.06 | 0.6131 |
| QT_GF1 | 17.88 | 507.6 | 0.1771 | 21.07 | 0.8659 |
| QT_GF2 | 18.5 | 543.7 | 0.1772 | 20.77 | 0.8073 |
| QT_GF3 | 18.36 | 534.9 | 0.1705 | 20.84 | 0.8114 |
| QT_GF4 | 18.95 | 569.8 | 0.1701 | 20.57 | 0.7566 |

It can be observed from the table the proposed QT_GF provides higher value of the PSNR and SSIM over the existing ES-GSF architecture under different modes.

*C. Design metrics*

All the existing and proposed Gaussian filter architectures are implemented on Tanner v14.1.

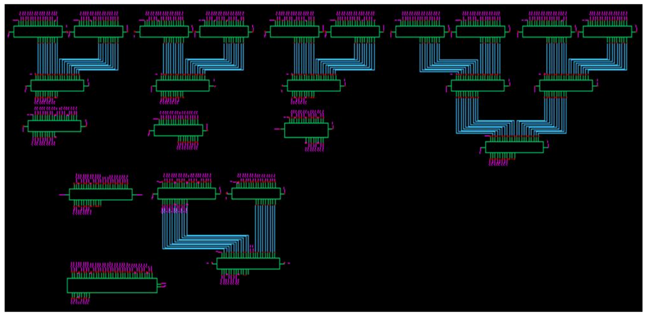


Fig. 11: Schematic of QT-GSF on Tanner.

The spice netlist is generated from the schematics implemented on Tanner. The design metrics such are area, power and delay are extracted for each design and are compared to evaluate the effectiveness of proposed architecture over the existing. The area, power, delay and energy metrics for the different GSFs are shown in Table 3.

TABLE 3: Design metrics for different GSF.

| Design | Area (#Tran) | Power (µw) | Delay (ns) | Energy (fJ) |
|---|---|---|---|---|
| MA-GSF | 5264 | 110.3 | 3.64 | 401.5 |
| GF_LASCAS | 5740 | 1050 | 4.38 | 4599 |
| ES-GSF | 5812 | 90.1 | 1.73 | 155.8 |
| QT-GSF | 6204 | 89.6 | 1.6 | 143.36 |

It can be observed from the Table that the proposed filter requires little more area due to exhibiting configurability feature over the existing filter architectures. The proposed design requires smallest power comparison over all the existing filter architectures. The proposed filter design shows 18.7%, 91.4%, and 0.7% reduced power consumption over the MA_GSF, LASCAS_GSF and ES-GSF architectures respectively. Thus, the proposed design is power efficient.

In order to evaluate the efficacy of the proposed design under different quality modes, the designs are simulated with varying kernel sizes and the simulation results are tabulated in Table 4. It can be observed from the simulation results that proposed QT-GSF provides significant energy saving when operated in the energy saving mode. When compared to the existing energy scalable Gaussian filter architecture, the proposed filter requires small energy consumption in each quality mode of operation.

TABLE 4: Design metrics under different modes.

| | Power(µw) | Delay(ns) | Energy(pJ) |
|---|---|---|---|
| ES-GSF00 | 90.1 | 1.73 | 155.873 |
| QT-GSF00 | 89.6 | 1.6 | 143.36 |
| ES-GSF01 | 89.9 | 2.52 | 226.548 |
| QT-GSF01 | 90.2 | 2.53 | 228.206 |
| ES-GSF02 | 89.6 | 2.92 | 261.632 |
| QT-GSF02 | 89.2 | 2.19 | 195.348 |
| ES-GSF03 | 89.9 | 2.98 | 267.902 |
| QT-GSF03 | 90.5 | 2.5 | 226.25 |

From the simulation results it can be observed that the proposed filter provides significant reduction in power, delay and energy consumption at the cost of small increase in the implementation area.

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## V. CONCLUSION

In this paper, an attempt has been made to achieve new quality tunable Gaussian filter architecture that provides better quality-energy trade-off over the existing filter architectures. Since the energy/power consumption of the filter increases with increasing kernel size, in the proposed approach, Gaussian kernel of different sizes are considered. An architecture is proposed that can compute filtered pixel using either 5x5, 3x5, 5x3, 3x3 size of kernel coefficient. The proposed and existing filter designs are implemented, simulated and design metrics are evaluated. The simulation results show that proposed filter provides 91.4% and 63.47% reduced power and delay over the existing filter architecture. Further, the quality metrics of the proposed filter are higher and filtered images are of acceptable quality

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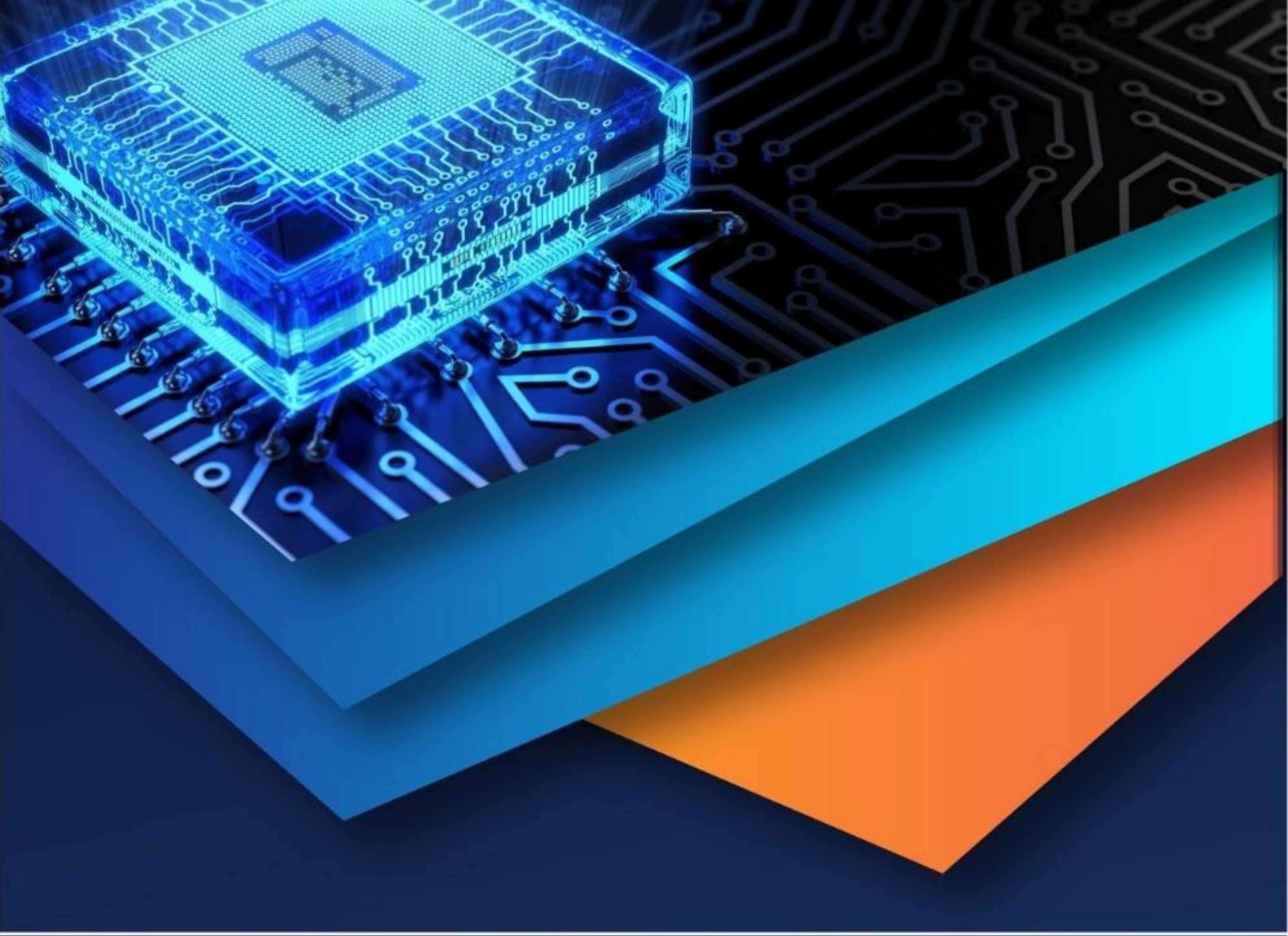


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