FOREX Publication
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International Journal of Electrical and Electronics Research (IJEER)
Research Article | Volume 10, Issue 4 | Pages 1036-1042 | e-ISSN: 2347-470X

A Novel Hexagonal Psuedo framework for Edge Detection Operators on Hexagonal Framework

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ABSTRACT- Edge detection using a gradient-based detector is a gold-standard method for identifying and analyzing different edge points in an image. A hexagonal grid structure is a powerful architecture dominant for intelligent human-computer vision. This structure provides the best angle resolution, good packing density, high sampling efficiency, equidistant pixels, and consistent connectivity. Edge detection application on hexagonal framework provides more accurate and efficient computations. All the real-time hardware devices available capture and display images in rectangular-shaped pixels. So, an alternative approach to mimic hexagonal pixels using software approaches is modeled in this paper. In this research work, an innovative method to create a pseudo hexagonal lattice has been simulated and the performance is compared with various edge detection operators on the hexagonal framework by comparing the quantitative and qualitative metrics of the grayscale image in both square and hexagonal lattice. The quantitative performance of the edge detection on the hexagonal framework is compared based on the experimental facts. The pseudo-hexagonal lattice structure assures to be aligned toward the human vision.

Keywords: Edge detection operators, Resampling, Spiral addressing architecture, Sampling efficiency, Grayscale image.

ARTICLE INFORMATION
Author(s): Prathibha Varghese and Dr.G. Arockia Selva Saroja;
Received: 21/08/2022; **Accepted:** 24/10/2022; **Published:** 20/11/2022;
E- ISSN: 2347-470X
Paper Id: IJEER 22701
Citation: 10.37391/ijeer.100446
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-10/ijeer-100446.html

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1. INTRODUCTION

This study discusses hexagonal image processing, a less-known sophisticated image processing approach. Despite the fact that this field of study has been explored for the past 40 years, most of the imaging systems currently in use utilize square lattice rather than hexagonal owing to how simple it is to construct. The hexagonal lattice is the best sampling strategy for circularly band-limited digital signals, providing 13.4% fewer samples than the square lattice, according to the multidimensional sampling theory [1]. In terms of geometric qualities, such as a higher level of symmetry, equal spacing, and uniform connectivity with its six-neighbours, the hexagonal lattice is indeed preferable to ordinary square lattice [2]. There is a need for innovative techniques to acquire hexagonal images in order to get over these fundamental restrictions in square lattice systems.

Hexagonal structures are inspired by nature, which accomplishes this in various ways. Since hexagonal pixels closely resemble the form of the human fovea, there is a strong correlation between hexagonal systems and human sensory systems. And, here is the basic explanation of how the human eye captures images to help make the link. The retina is a delicate membrane located inside the back of the eye. The retina's goal is to collect light information, which the brain then translates into neural impulses for visual identification.
The fovea is a tiny region of the retina. The fovea's structural design is hexagonally positioned and has a highly dense conical shape, which acquires clearer vision than a square grating arrangement. As per [3], [4], [5], [6], the structure of the hexagonal lattice offers an additional advantage over the square lattice when detecting straight and circular edges, which provides a higher accuracy [6]. This results in greatly improved precision of circular and near-circular images when processed [7].

Another key factor in this digital imaging technology is spatial sampling efficiency. The spatial sampling efficiency by the hexagonal structure is superior over a rectangular grid of similar pixel separation, which reflect better computation and fewer (13% less) pixel requirement to achieve the same image resolution when compared to a rectangular grid. Fadaei & Rashno [8] proposed an efficient simulation approach for converting square to hexagonal lattices. Xiangguo Li [9] also proposed a hexagonal lattice conversion algorithm using a 1-D interpolation kernel rather than a 2-D interpolation kernel.

Edge detection and image enhancement are the two areas in which computer vision concepts expand and will require increasing demand to know the structure of the irregular curves contained in that image. Consequently, it is of vital significance resulting in dissimilar methods for identifying the structure of an image, so the first step in the process of computer vision is edge detection. Most of the algorithm's efficiency is limited to curved structural features. The promising solution to overcome this difficulty is to represent the images using an alternate sampling grid called a hexagonal grid framework.

A hexagonal sampling scheme provides good angular resolution, consistent connectivity, equidistant property, fixed neighborhood connectivity, reduced aliasing effect, etc [10]. Hexagonal pixels are more suitable for human vision as they replicate the structure of rods and cones in our human eyes [11]. This structure provides less sensitivity in the diagonal direction than in the horizontal direction. Hence, in this paper, we present a diverse structure to process the hexagonal sample image and show different important characteristics: square-to-hexagonal image conversion, and detecting edges using different edge detection algorithms in both grids. More importantly, we would like to prove that hexagonally sampled images are a better sampling grid in the edge detection image processing field.

In this paper, the authors initiate a research objective conducted by a review of some hexagonal grid image processing algorithms in *Section 2*. *Section 3* deals with different resampling techniques for hexagonal image representations. *Section 4* deals with the features of different edge detection operators. *Section 5* gives a detailed review of the methodology implementation used in the proposed work. *Section 6* deals with performance evaluation, and *Section 5* gives the conclusion.

2. RESEARCH OBJECTIVES

Numerous edge detection and hexagonal image processing algorithms have been studied and investigated in the past years by researchers in this area. But the combination of these methods has not been discussed in the forefront because of the unavailability of hardware to capture and display the hexagonal images. To alleviate this problem, images in the rectangular grid are converted into the hexagonal grid using software coding. Briefly, the objectives are as follows:

(1) To create a hexagonally-sampled image processing system, that involves the acquisition, resampling, and conversion of rectangular to hexagonally-sampled images on the hexagonal grid of images.

(2) Several edge detection conventional gradient-based operators such as Robert, Sobel, Log, Prewitt, and Canny are applied to the pseudo-hexagonal image.

(3) Performance comparisons of these hexagonal and rectangular grid images are made on edge detection algorithms.

3. HEXAGONAL IMAGE REPRESENTATION RESAMPLING METHODS

Hexagonal image processing has predominantly many advantages but it is not used in the practical world owing to the lack of imaging sensors like Charge-coupled devices (CCDs) and display systems. But fortunately, there are different ways to simulate hexagonal images by resampling from the original square grid. Different resampling techniques are discussed below.

3.1 Hexagonal Image Processing (HIP) Framework and Algorithms

Let f (x_1, x_2) represents an image, $f_s(x_1, x_2)$ represent the sampled image, and h(x) signify the sampling kernel. The image sampling can be represented by,

$$x_h(k_1,k_2) = \sum_{n_1} h_{r1}\left(\left(k_1 - k_1 - \frac{1}{2}k_2\right)T_{h1} - n_1 T_{s1} x_s(n_1,k_2)\right) \quad (1)$$

Here 2-Dinterpolation occurs at the horizontal path. Therefore, 2-Dimensional interpolation could be reduced to 1-Dimensional interpolation. At this point, it is to be noticed that, interpolation is executed at the horizontal path as seen in *Figure 1*.

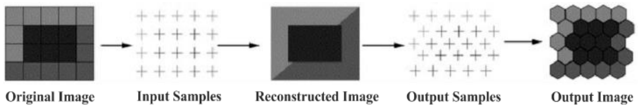

Figure 1: Hexagonal grid resampling

3.2 Virtual Spiral Hexagonal Structure

Ma et al. [12] constructed an architecture of the virtual spiral that prevails during the hexagonal image processing mechanism as shown in *Figure 2*. The resulting results can be mapped using this virtual grid hexagonal structure and transformed back into a square grid structure. Lastly, results can also be returned to the Rectangular grid from the spiral architecture, as shown in *figure 2*. The main highlight of this method is that it maintains good resolution without any distortion. At the same time, the disadvantage is its high computational cost occurring during conversion.

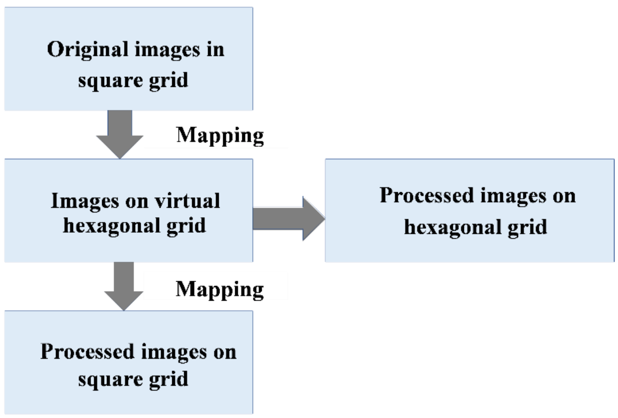

Figure 2: Virtual hexagonal structure

3.3 Pseudo hexagonal pixel structure

Lattice or grid represents different tiling or tessellation schemes. Let B = $\{b_1, b_2\}$ be the basis real vectors of the rectangular plane. Lattice is defined by set B as shown in *equation 2*,

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$$L_B = \{n_1 b_1 + n_2 b_2 : n_i \in Z, i = 1,2\} \quad (2)$$

Different basis vectors are there for the generation of dissimilar lattices.
For example, B_s= {(1,0), (0,1)} gives square lattice. The predominant grids for generating hexagonal ones are,

$$B_{H1} = \left\{(1,0), \left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right)\right\} \quad (3)$$

$$B_{H2} = \left\{\left(\frac{\sqrt{3}}{2}, \frac{1}{2}\right), (0,1)\right\} \quad (4)$$

By deriving the relations between B_{H1} and B_{H2}, only b_2 is altered which shows that horizontal spacing is the same as seen in *figure 3*.

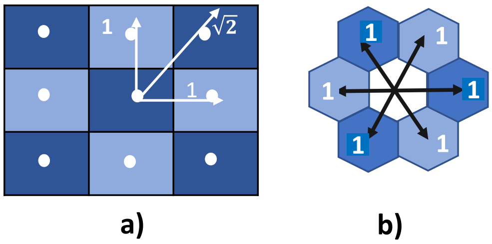

Figure 3: Representation of spacing arrangement of (a) square, and (b) hexagon

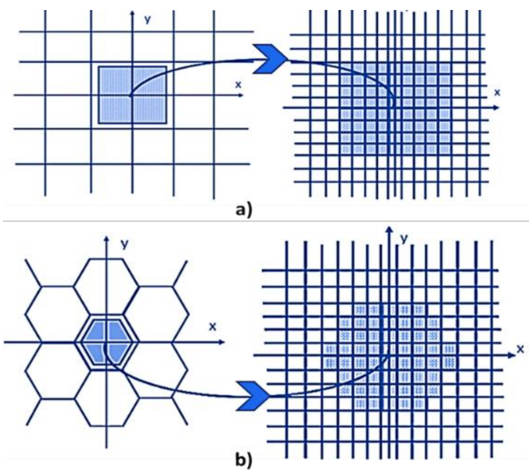

Figure 4: Hyper pixel simulation (a) square, and (b) Hexagon

Using the best grid vectors discussed above, Middleton & Sivaswamy [13], and Sivaswamy [14] designed a new hexagonal framework for simulating hexagonal grid pixels for hexagonal-image processing, in which re-sampling of the image will generate a hexagonally sampled pixel image as shown in *Figure 4*. Hexagonal sampled images generated will have a powerful resolution. Čomić & Nagy [4] also introduced a pseudo hexagonal structure with an arrangement of square pixels.

3.4 Mimic hexagonal structure

A mimic hexagonal structure consisting of 4 square pixels, and its pixel values are calculated by averaging the four-square pixels for the hexagonal image framework as shown in *Figure 5*, as proposed by Coleman et al. [15].

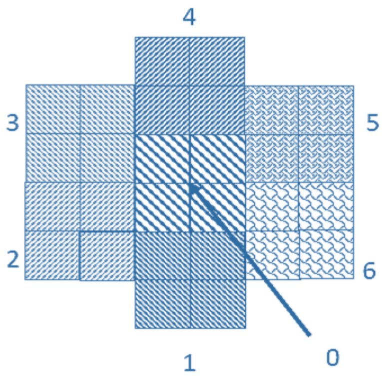

Figure 5: A cluster of seven mimic hexagons

This scheme preserves the six neighborhood designs, but it does not follow the equidistant property. This method provides less resolution as the average of four pixels is taken as the grey value.

4. EDGE DETECTION OPERATORS

Edge detection is an effective method for the improvement and detection, feature elimination, and detection of images to identify sudden changes in the light of sharp changes in image luminosity and discontinuities. As the identification of the edges is an active field of study, detailed image analysis is possible. In the grey level image, for example, point, line, and edges, there are three types of discontinuities. All three types of image discontinuities can be defined through spatial masks [13]. The edge detection segment addresses the most frequently used discontinuities in image processing. Roberts, Sobel, Prewitt, Log, and canny edge detection are the most popular edge detection gradient operators in this category as shown in *Figure 6.* The edge detection detects variations with differential operators in different grey-level gradients. It is broken down into two major categories [12], [16-20]:

Gradient – Sobel operator, Prewitt operator, Robert operator – computes first–order derivative images on a digital image, and **Gaussian –** Canny Edge Detector, Laplacian of Gaussian dependent operator – calculates the second-order derivatives on a digital image.

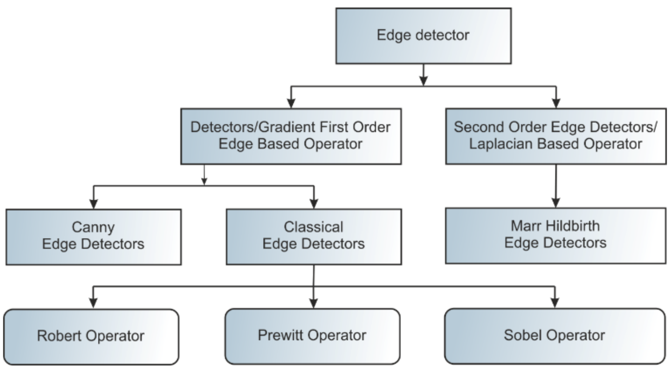

Figure 6: Types of edge detectors

4.1 Sobel edge operator

It is a discerning distinguishing operator. For the detection of the edge of the image, the gradient approximation is calculated.

The Sobel operator normally or the appropriate gradient vector is generated in the pixels of the image. In calculating derivative approximations of vertical or horizontal derivatives, it uses two kernels or masks 3 x 3 combined with the image data. Therefore,

$$M_x = \begin{pmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{pmatrix} M_y = \begin{pmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{pmatrix} \quad (5)$$

4.2 Prewitt operator
This operator shows a similar performance as that of Sobel. This operator provides a correct method to find out the magnitude and orientation of edges in an image. Kernels of this operator respond to the 45 degrees more accurately using these kernels or masks.

$$M_x = \begin{pmatrix} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{pmatrix} M_y = \begin{pmatrix} -1 & -1 & -1 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{pmatrix} \quad (6)$$

4.3 Robert operator
In this gradient-based operator, the number of squares is determined with discrete distinguishing between pixels in an image diagonally adjacent. The approximation of the gradient is performed at that point. The subsequent 2 x 2 kernels or masks are utilized,

$$M_x = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} M_y = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \quad (7)$$

4.4 Laplacian of Gaussian (LoG)
The Laplacian operator uses the second image derivative. It is a Gaussian operator. This gradient operator performs fine when there is a rapid-intensity transformation occurs. It mainly concentrates on the zero-crossing detection rule, i.e., if the derivative of the second order crosses zero, the max level corresponds to that particular location. The location is named on the rim. In this case, the Gaussian gradient operator eliminates the random noise, and the Laplacian operator defines the sharp abrupt edges.

The Gaussian function is defined using the following formula,

$$G(x,y) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp - \left(\frac{X^2 + Y^2}{2\sigma^2} \right) \quad (8)$$

Where σ is the normal deviation. And the operator from LoG is determined using the expression below,

$$LoG = \frac{\partial^2}{\partial x^2} G(x,y) + \frac{\partial^2}{\partial y^2} G(x,y) = \frac{x^2 + y^2 + 2\sigma^2}{\sigma^4} \exp\left(-\frac{X^2 + Y^2}{2\sigma^2} \right) \quad (9)$$

4.5 Canny operator
It is an edge detection operator based on Gaussian. This operator has no sensitivity to noise. It extracts picture features without altering the purpose or affecting them. The Canny edge detector offers an innovative algorithm derived from the Gaussian operator's earlier work, Laplacian which is a powerful edge detection operator. The most well-known method is used for optimal border detection. It senses the edges in three ways:
(1) Error rate reduction.
(2) Edge points shall be precisely located.
(3) Only one edge detection can occur.

5. IMPLEMENTATION OF THE PROPOSED METHODOLOGY
A common and effective analysis method utilized in image processing tasks is edge detection. A hexagonal grid hexagonal image processing (HIP) architecture is used to examine the edge detection algorithm, as depicted in the schematic diagram in *Figure 7*. The following steps are used in the edge detection based on the hexagonal grid:
Step 1: The image is re-sampled to a hexagonal domain using different software methods.
Step 2: Hexagonal image enhancement using the Gabor filter.
Step 3: Pass the images through various edge detection operators.
Step 4: Performance comparison of images in both hexagonal and rectangular grids.
Step 5: Calculation of qualitative and quantitative measures such as PSNR and MSE.

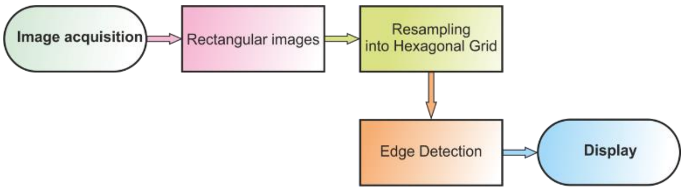

Figure 7: Block diagram of hexagonal-based edge detection

5.1 2 DIHLC Algorithm
The proposed pseudocode for the hexagonal lattice is given in *Table 1*. The hexagonal lattice framework is simulated utilizing the concept of sub-square pixels of size 6*6-pixel size.

Table 1: Pseudocode for the proposed hexagonal lattice

Inputs: Input square image (*jpg, *png, *tif)
Output: Hexagonal image
Parameters: Neighborhood size 6x6, pixel coefficients
Begin
// Identification Phase
Extract the size of the image
Select zero matrix of size 6x6
// Embedding Phase
Identify the pixel locations marked '1' and fill with given image intensity value as shown in *Figure 6*
Elaborate the zero matrix to fill the complete pixel intensity values by identifying locations of pixel marked '1'
Do shifting operations accordingly to generate cluster of hexagonal pixels without any overlapping and vacant spaces as shown in *Figure 7*
// Extraction Phase
Obtain hexagonal structured image with hexagonal pixel
End for
Return Hexagonal image
End

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5.2 JK Algorithm

Using the JK algorithm [21], each hexagonal pixel is made from 56 square pixels as shown in *Figure 8*. For developing a hexagonal pixel from the square pixel, a 9x8 matrix is considered, i.e., a total of 72 pixels. Out of these 72 pixels, pixels marked as '0' are discarded but only pixels marked '1' are used in the hexagonal pixel generation. This algorithm can be extended for color images also by superimposing three channels.

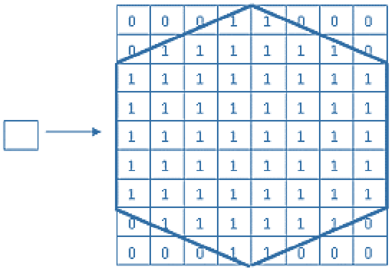

Figure 8: Psuedo hexagonal pixel from the square pixel

5.3 Alternate Pixel Suppressal Method (Resampling Method)

Pramod Sankar et al. [22], proposed an alternate pixel suppressal method in which a hexagonal pixel grid can be derived from a rectangular grid. The sub-sampling expression is,

$$pixel\_val_{hex(i,j)} = \begin{cases} pixel\_val\ (2*i, 2*j)\ \ if\ \ i\ \ is\ \ even \\ pixel\_val\ (2*i, 2*j+1)\ \ if\ \ i\ \ is\ \ odd \end{cases} \tag{10}$$

In this method, alternate pixels in the rows and columns are suppressed in the rectangular grid. During the processing stage, sub-sampled suppressed images cannot be considered for computation. The hexagonal pixel grid is displayed in *figure 9*.

(a) (b)

Figure 9: (a) Rectangular pixel grid, and (b) Hexagonal pixel grid

5.4 Half pixel shift method

To acquire hexagonal grids from the standard rectangular grids, a methodology was proposed on a half-pixel shift as described in [23]. In a half-pixel shift method, the midpoint between two adjacent pixels has to be identified for any odd line utilizing a single linear technique.

The mid-point value=(left_value+ right_value) / 2).

$$P^{new}(x,2y) = P^{old}(x,2y)$$
$$P^{new}(x,2y+1) = (P^{old}(x,2y+1) + P^{old}(x+1,2y+1))/2 \tag{11}$$

Figure 10 shows a hexagonal map of a square pixel or rectangular pixel grid using half-axis symmetry. In this method, the mid values are kept, discarding left and right values.

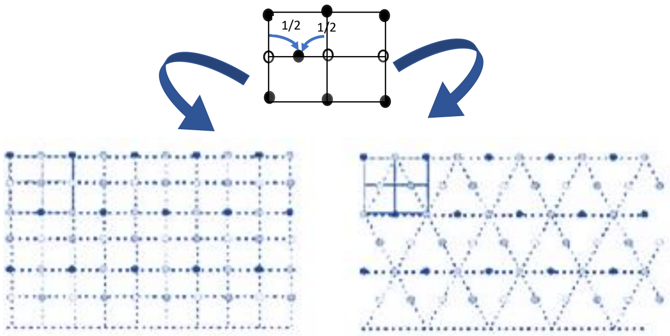

Figure 10: Half-pixel hexagonal grid

6. PERFORMANCE EVALUATION

In this research work, different edge detection gradient operators like Prewitt, Sobel, Robert, and Canny are compared on the real rectangular grid structure with the hexagonal grid structure; 8-bit grey-level multiple images with size *256x256* is taken as the sample images for the edge detection algorithms for both frameworks. In order to compare the computational efficiency, a comparison is made based on the Mean Squared Error (MSE) and Peak signal-to-noise ratio (PSNR).

6.1 Mean Squared Error

The mean value difference in the pixel in the picture is indicated by MSE. A higher MSE indicates a greater contrast. It is expressed as,

$$MSE = \frac{1}{N}\sum_i \sum_j (X_{ij} - V_{ij})^2 \tag{12}$$

Where *N* corresponds to the image size, the image is X and the initial image is *V*.

6.2 Peak Signal-to-Noise Ratio

A higher PSNR value indicates that the quality of the compressed or restored images is better. PSNR is used for the quantitative comparison [24]. MSE is inversely proportional to PSNR. Hence, PSNR could be mathematically expressed as,

$$PSNR = 10.LOG_{10}\left(\frac{n*255^2}{\sum_i \sum_J (X_{ij} - v_{ij})^2}\right) \tag{13}$$

7. RESULTS AND DISCUSSIONS

The classical standard edge detection gradient operators such as Robert, Sobel, Prewitt, Log, and Canny are highly sensitive to noise and very simple to design the kernels in the software. In the rectangular domain, grid structure edge detection operators show discontinuous edges.

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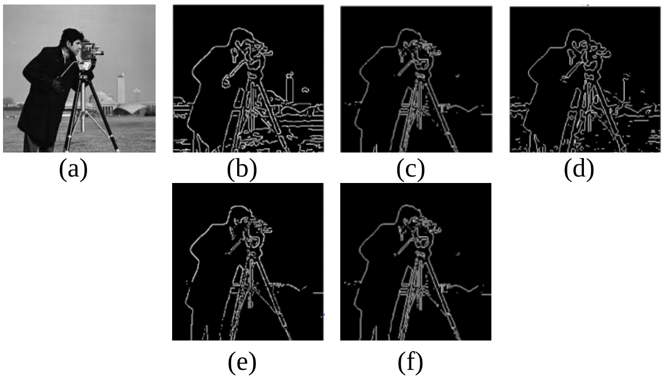

Figure 11: Rectangular grid-edge detection operators: (a) Original cameraman image, (b) Canny, (c) Prewitt, (d) Log, (e) Robert, and (f) Sobel

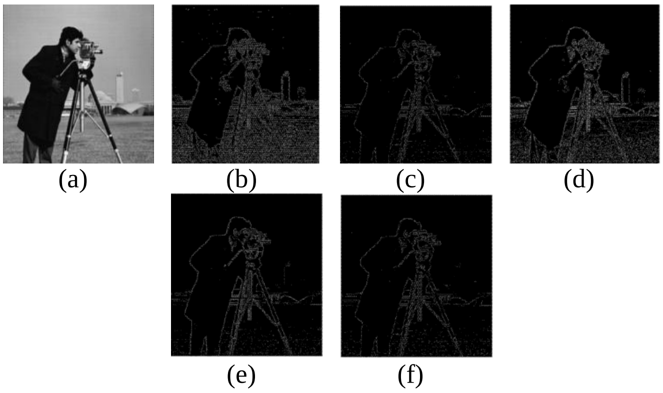

Figure 12: Half-pixel method (Resampling method): (a) Hex cameraman image, (b) Canny, (c) Prewitt, (d) Log, (e) Robert, and (f) Sobel

Table 2: Performance comparison of edge detection operators in rectangular lattice and hexagonal lattice

Method	Sample Image	Operator	MSE	PSNR
Resampling Method	Cameraman.jpg	Robert	30.87	32.63
		Sobel	30.22	32.89
		Prewitt	32.71	31.02
		Log	32.69	31.89
		Canny	29.66	33.93
Rectangular Grid	Cameraman.jpg	Robert	31.98	30.05
		Sobel	32.93	32.99
		Prewitt	33.88	28.98
		Log	34.24	32.95
		Canny	31.79	32.94

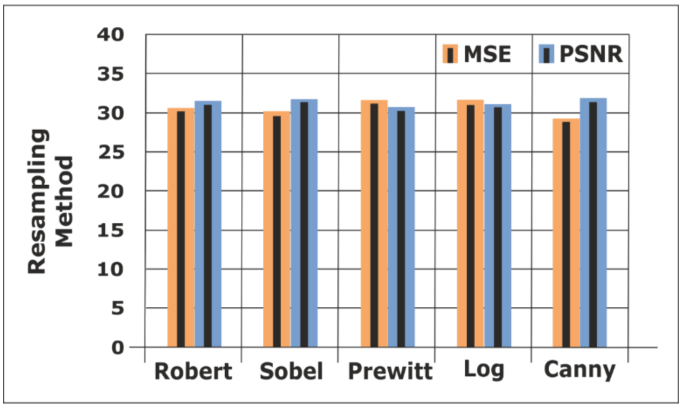

Figure 13: MSE and PSNR Assessment using Resampling Method

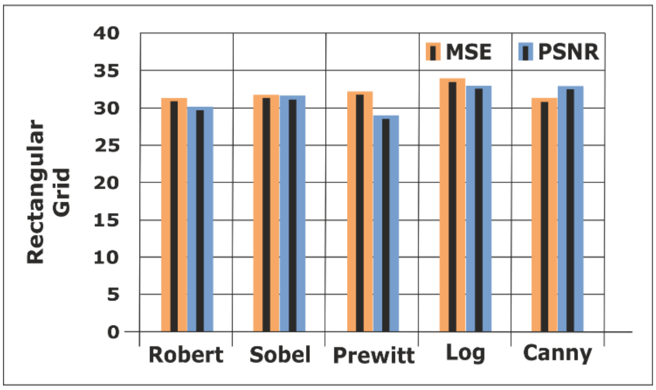

Figure 14: MSE and PSNR using Rectangular Grid

The outputs of different edge detection operators on the rectangular domain and hexagonal domain are shown in *figure 11* and *figure 12*. The performance comparison based on MSE and PSNR is also shown in *table 2, figures 13-14.*

8. CONCLUSIONS

In this paper, various edge detection operators' design procedure for edge detection in hexagonal and rectangular grid structure is compared. As there are not enough advanced hardware devices to capture hexagonal images, a software approach is used for simulating the pseudo hexagonal images and resampling and resizing these rectangular images. MSE and PSNR values which are used for comparison showed that the edge detection operator on the hexagonal domain is superior to the rectangular domain based on both the objective-wise and subjective-wise quality. The only limitation of this work is the lack of hexagonal lattice display and capture device hardware. A comparison of both grids revealed that the pseudo hexagonal method has outperformed the rectangular grid edge detection method. In the future, the proposed pseudo hexagonal lattice structure will be applied to several image processing algorithms and will be recommended as the future scope of hexagonal framework structures.

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