New Wavelet Domain Wiener Filter Based Denoising for Poisson Noise Removal in Low-Light Condition Digital Image (OTSU WIE-WATH)

S.Suhaila[1, 2], Y. Y. Chia[1], R. Ibrahim[3], R. Hazli[4] and N. S. A. M. Taujuddin[1,2]

[1]*Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Johor, Malaysia.*

[2]*EmbCos Research Group, Universiti Tun Hussein Onn Malaysia, 86400 Johor, Malaysia.*

[3]*Faculty of Computer Science and Information Technology, Universiti Tun Hussein Onn Malaysia, 86400 Johor, Malaysia.*

[4]*Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 86400 Johor, Malaysia.*

suhailas@uthm.edu.my

***Abstract*—Digital imaging was developed as early as 1960s, largely to avoid the operational weaknesses of film cameras, for scientific and military missions. As digital technology became cheaper in later, digital images become very common and can simply captured using camera embedded in smartphone nowadays. Nevertheless, due to the limitation of camera technologies in low cost development, digital images are easily corrupted by various types of noise such as Salt and Pepper noise, Gaussian noise and Poisson noise. For digital image captured in the photon limited low light condition, the effect of image noise especially Poisson noise will be more obvious, degrading the quality of the image. Thus, this study aims to develop new denoising technique for Poisson noise removal in low light condition digital images. This study proposed a method which is referred to the OTSU WIE-WATH Filter which utilizes Otsu Threshold, Wiener Filter and Wavelet Threshold. This filter is designed for low and medium Poisson noise removal. The proposed filter performance is compared with other existing denoising techniques. These filters performances are analyzed with two evaluation methods which are objective method and subjective method. Objective method includes performance analysis in terms of Peak Signal to Noise Ratio (PSNR) and Mean Squared Error (MSE). On the other hand, subjective method used is visual effect inspection. The results show that proposed OTSU WIE-WATH Filter provide better performance than compared denoising techniques in low and medium levels Poisson noise removal while preserving the edges and fine details of noisy images.**

***Index Terms*—Denoising; Low Light Condition; Poisson Noise; Threshold.**

I. INTRODUCTION

Digital image processing is a part of signal processing field to enhance or modify digital data using computer and its final target is to improve image quality [1]. Noise often degrades quality of image especially image captured in low light condition. Digital cameras use higher ISO rating to increase the sensitivity towards light in capturing low light condition image but at the same time introduce more noise to the image [2]. The quality of an image captured without flash is often corrupted by noise and motion blur. Different types of noise will corrupt image in different ways, thus different methods are used to deal with different types of noise effectively [3].

Image filtering is an effective denoising technique commonly used. The decision to apply a particular filter is based on the noise level of noisy image and the performance of the filter which is used on a filtering mask [1]. Several types of filter such as Linear Filters (for example Mean Filter and Wiener Filter), Non-Linear Filters (for example Bilateral Filter [4], Median Filter [5], Maximum Filter and Minimum Filter), and Adaptive Filters (for example Adaptive Median Filter) can be used in image denoising.

Even in this new era, most consumer cameras have poor low-light characteristics, which are then result in low-light condition images corrupted by noticeable noise. The Poisson noise becomes dominant source of noise in low light condition due to limited photon in weak light source.

There are few researches specified for Poisson noise removal in low light digital image. Besides, most researchers faced problems such as long computational time, loss of image details and edges. Therefore, this study aims to develop technique which effectively reduce Poisson noise in low light condition digital image.

II. LITERATURE REVIEW

In one of the previous research on image denoising technique using hybrid filtering scheme, both Wavelet Thresholding and Bilateral Filtering are performed [6]. The performance of the proposed method is significantly improved than Bilateral Filter in most noise levels in terms of PSNR and MSE.

A study on “Improved Kuwahara Filter Based Denoising for Poisson Noise Removal in Low Light Condition Digital Image” [7] had proposed three denoising techniques. These techniques named Otsuhara, Ku-Wath and Otsuhara-Wath which utilize several filtering methods and achieve a fast and effective Poisson noise removal way compared to previous techniques, but the improvement in terms of PSNR and MSE are not high enough when compared to conventional Kuwahara filter.

M. Siddeq [8] had proposed to denoise image using the combination of Discrete Wavelet Transform (DWT) and Wiener filter, the proposed technique also estimate the noise power. The DWT transforms noisy image into sub-bands, contain low and high-frequencies. Then, it estimates noise power for each sub-band. After compute the variance apply the Wiener filter on each sub-band by using local window $n \times n$, finally inverse DWT is performed to obtain the resultant denoised image. The advantage of this filter is that it is able to prevent blurred image as filtered by conventional Wiener filter but it takes a longer computational time than conventional Wiener and DWT methods.

In conclusion, there are numerical techniques proposed by researchers to reduce noises in images but few of them are specified for denoising low light digital image especially image contaminated by Poisson noise. This is the reason that denoising techniques particularly for Poisson noise removal in low light condition digital image is proposed in this study. Besides, hybridization filtering scheme which utilize several filtering method show significant success in most previous research, thus this scheme is also used in this study to obtain a better denoising result.

For proposed method in this study, three conventional techniques utilized, which are Otsu Threshold [7], Wiener Filter and Wavelet Threshold [7]. Otsu Threshold is used to divide the smooth and texture regions of the image. Wiener filter is a filter that proven to remove Poisson noise effectively when compared to mean filter and median filter [9]. Wavelet Threshold is an effective denoising method that often used to remove image noise. Studies in [6], [7] and [10] utilized wavelet threshold technique to remove Poisson noise effectively.

III. METHODOLOGY

In this section, the proposed method is discussed in detail. This study proposed a denoising technique referred to as the OTSU WIE-WATH Filter which utilizes the Otsu Threshold, Wiener Filter, and Wavelet Threshold for effective low and medium level Poisson noise removal. This technique utilizes hybridization filtering scheme which combine several denoising methods to eliminate Poisson noise. The denoising techniques will be applied to noisy image captured in low light condition.

The processing of test images involves addition of Poisson noise with different scales to clean test images to form noisy images. The process of adding Poisson noises on images to be tested is needed because the pair of original clean image and resultant denoised image is both utilized while doing denoising performance analysis. The test images are clean low light condition digital images that are almost free from any noises. These images are captured using DSLR camera which able to capture high definition images. Next, the addition of Poisson noise with different scales to the test image is performed. The input digital image in program codes is changed to double precision to scale up the Poisson noise by 1e12 so that Poisson noise of different scales can be inserted. This study utilizes 6 scales of Poisson noise which are further divided into three categories: 1e7, 5e7 and 1e8 represent low noise level; whereas 5e8, 1e9 and 5e9 represent medium noise level, respectively. The noisy image, $f(i,j)$, is produced based on the scale that is applied on the original image, $ori(i,j)$. In real imaging systems, photon noise and other sensor-based sources of noise contribute in varying amounts at different signal levels, producing noise which is dependent on scene brightness. For large photon counts, Poisson distribution approaches a normal distribution about its mean, usually making shot noise in actual observations indistinguishable from true Gaussian noise [11]. Figure 1 shows the kl.jpg test image added with 6 different scales of Poisson noise.

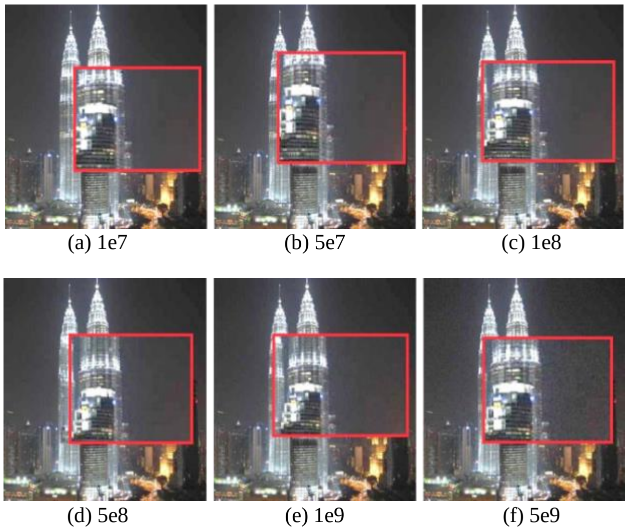

Figure 1: The noisy kl.jpg test image with low (1e7, 5e7 and 1e8) and medium (5e8, 1e9 and 5e9) level of Poisson noise (the areas in the red boxes are enlarged region of the image to show noise level differences.)

A. *Otsu Threshold*

The Otsu Threshold [12] is applied to the noisy image to separate texture region, r, and smooth region, q, of the noisy image. The application flowchart of Otsu Threshold on noisy images is shown in Figure 2.

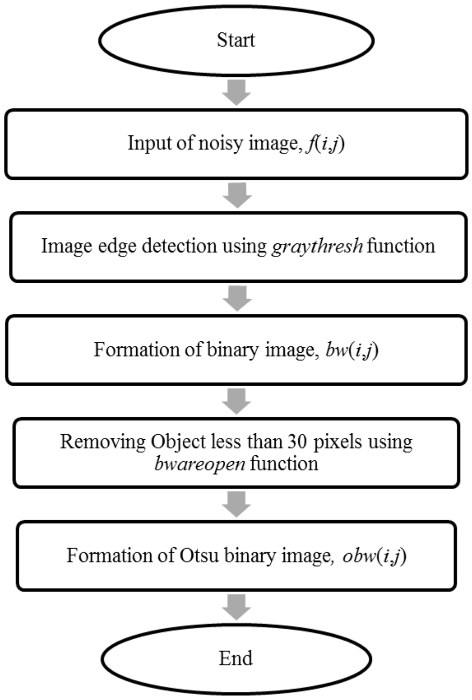

Figure 2: Process flowchart for applying Otsu Threshold

After insertion of noisy image, image edge detection using graythresh function will be applied on the noisy image, $f(i,j)$. The *graythresh* function chooses the threshold to minimize the intraclass variance of the black and white pixels which has setting values at [0 1], the color noisy image will turn into grayscales image. Then, the grayscale image will be threshold into binary image, $bw(i,j)$.

There are two processes involved in thresholding process which are minimizing the weighted variance within class variance and maximizing weighted variance between class variance. Equation (1) is applied for the first process and Equation (3) is applied for the second process. After that, *bwareopen* function is used to remove the connected components (objects) that have value smaller than the connected component threshold, *T1*. The *T1* value is used as a parameter setting to reduce the connected component in image while avoiding the losses of image details.

The weighted variance within class variance, $\sigma_v^2(T_1)$, can be minimized by:

$$\sigma_v^2(T_1) = v_q(T_1)\,\sigma_q^2(T_1) + v_r(T_1)\,\sigma_r^2(T_1) \quad (1)$$

The class probabilities, $v_q(T_1)$ and $v_r(T_1)$ can be estimated by:

$$v_q(T_1) = \sum_{z=0}^{T-1} p(z) \text{ and } v_r(T_1) = \sum_{z=T1}^{L-1} p(z) \quad (2)$$

where:

$p(z)$: Gray levels
L : Range of intensity levels
T_1 : Class probabilities equal to [1, 256]
$\sigma_v^2(T_1)$: Weighted variance within class variance
$\sigma_q^2(T_1)$: Variance of pixels in background
$\sigma_r^2(T_1)$: Variance of pixels in foreground

The weighted variance between class variance, $\sigma_B^2(T_1)$, can be maximized by:

$$\begin{aligned}\sigma_B^2(T_1) &= \sigma_{class}^2(T_1) - \sigma_v^2(T_1)\\ &= v_q(T_1)\,[\mu_q(T_1) - \mu_{class}]^2 + v_r(T_1)\,[\mu_r(T_1) - \mu_{class}]^2\\ &= v_q(T_1) - v_r(T_1)\,[\mu_q(T_1) - \mu_r(T_1)]^2\end{aligned} \quad (3)$$

where:

$\sigma_{class}^2(T_1)$: Combined classes variance
μ_{class} : Combined classes mean
$\mu_q(T_1)$: Mean of pixels in background
$\mu_r(T_1)$: Mean of pixels in foreground

B. Wavelet Domain Wiener Filter (WIE-WATH)

WIE-WATH Filter utilizes Wavelet Threshold and Wiener Filter [8]. At first, the Discrete Wavelet Transform (DWT) transforms noisy image into sub-bands, contain low-frequencies and high-frequencies, and then noise power for each sub-band are estimated. The noise power is calculated through two important computations: calculate square of variance for each sub-band then calculate the mean of the variance. After computing the variance, Wiener filter is apply on each sub-band by using local window $n \times n$. Lastly, the inverse DWT (IDWT) is performs to obtain the denoised image, as shown as Figure 3.

The Wavelet Threshold [8] is a signal estimation technique, it uses the capabilities of wavelet transform for signal denoising. An image can be decomposed into a series of different spatial resolution images using DWT. In case of a 2D image, 2-level decomposition can be accomplished resulting different frequency bands namely, LL, LH, HL and HH. The sub-image LL is produced by computing the trends along rows of the image followed by computing trends along its columns. In the similar manner, fluctuations are also created by calculating trends along rows followed by trends along columns. The next level of wavelet transform is applied to the low frequency sub band image LL.

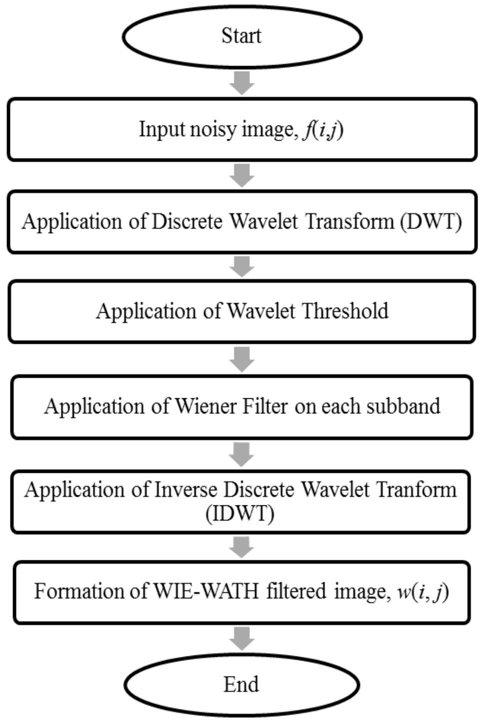

Figure 3: Flowchart for application of WIE-WATH Filter

The Wavelet Threshold is applied on the noisy image, $f(i,j)$. Before further process, $f(i,j)$ is transformed to wavelet domain by using the DWT. The Bayes soft threshold as defined in Equation (4) to Equation (7) are used for recognizing the important characteristics in the image like edges, details and textures of that image. Bayes soft threshold is defined by:

$$t_B = \frac{\sigma^2 u(i,j)}{\sigma^2 ori(i,j)} \quad (4)$$

$$\sigma^2_{f(ij)} = \frac{1}{M^2}\sum_{f=1}^{M} A_m^2 \quad (5)$$

$$\sigma_{ori(ij)} = \sqrt{\max(\sigma^2_{f(i,j)} - \sigma^2_{u(i,j)}, 0)} \quad (6)$$

where:

t_B : Bayes Threshold
$\sigma^2_{ori\,(i,j)}$: Variance for original image
$\sigma^2_{f\,(i,j)}$: Variance for noisy image
A_m : Wavelet coefficients for subband
M : Total number of wavelet coefficients in subband

Since the original image are usually unknown, the variance of the original image, $\sigma^2_{ori\,(i,j)}$ can be estimated by:

$$\sigma^2_{f\,(i,j)} = \sigma^2_{ori\,(i,j)} + \sigma^2_{u\,(i,j)} \quad (7)$$

where:

$\sigma^2_{u\,(i,j)}$: Variance for noise (median(|$HH_{f(i,j)}$|)/0.6745)

The Bayes soft threshold is used to denoise the wavelet coefficients thoroughly. Next, IDWT will help to reconstruct the noisy image, $f(i,j)$. Finally, the Wavelet filtered noisy image, $u(i,j)$ is produced.

The Wiener filter [8] is used to eliminate Gaussian noise from a corrupted image based on statistics estimated from a local neighborhood of each pixel. This filter depends on the noise power (i.e. noise variance in a noisy image). When the variance is large, the filter performs little smoothing. Conversely, when the variance is small, the filter performs more smoothing; this filter often produces better results than other filtering used for image enhancement. In this study, this filter is used with local window $n\times n$ applied on the DWT from each subband to remove Gaussian noise. The Wiener filter is shown in the following equations:

$$\mu_g=\frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}f(i,j) \quad (8)$$

$$\sigma_g^2=\frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}f^2(i,j)-\mu_g^2, (\text{ Note: } n=3,5,7) \quad (9)$$

where:

μ_g : Local mean

σ_g^2 : Local standard deviation

The Equations (8) and (9) are used to estimate local mean and local standard deviation, for local window $n\times n$ at noisy sub-band. Finally, Wiener filter is applied for each coefficient inside local window $n\times n$ to obtain denoised coefficients. Then the local window moved one step from left to right to obtaining new denoised coefficients $D(i,j)$ shown in the Equation (10):

$$D(i,j) = \mu_g + [(\sigma_g{}^2 - \tilde{n})/ \sigma_g{}^2]\,[f(i,j) - \mu_g] \quad (10)$$

where:

$\tilde{n}$: Wiener factor for noise power estimation

C. Proposed Method: OTSU WIE-WATH Filter

Proposed method, OTSU WIE-WATH Filter is developed by combining Otsu Threshold, Wavelet Threshold and Wiener Filter. This method is proposed due to the proved effectiveness of WIE-WATH Filter in removing Gaussian noise [8]. This WIE-WATH Filter is better than conventional Wavelet thresholding method in Gaussian noise removal [8]. The result for Poisson noise removal is worth tested since Poisson noise approaches Gaussian distribution in large photon count [11].

This proposed method is able to reduce noise in smooth region of noisy image while texture region of noisy image remain unchanged. While applying this method, first of all, the noisy low light image, $f(i,j)$ will be inserted and Otsu Threshold is applied to the noisy image to produce an Otsu binary image $obw(i,j)$. The Otsu binary image consist of level 1 which represents texture regions and level 0 which represents smooth regions. Then WIE-WATH Filter will be applied on the smooth regions of noisy image, $f(i,j)$ based on the location of level 0 in the Otsu binary image $obw(i,j)$.

On the other hand, the noisy image, $f(i,j)$ pixel values will be use directly on the texture regions based on the location of level 1 in the Otsu binary image $obw(i,j)$. Finally, the OTSU WIE-WATH image, $ow(i,j)$ is produced by the combination of noisy image, $f(i,j)$. and the WIE-WATH filtered image, $w(i,j)$. The process flowchart of this proposed OTSU WIE-WATH Filter is shown in Figure 4.

OTSU WIE-WATH Filter only denoises the smooth regions of noisy images using the combination of Wiener filter and Wavelet Threshold (WIE-WATH filter) and the texture regions remain the same as the original noisy image pixels. The proposed filter allows the noisy pixels in the dark regions to be removed while preserving the texture regions to avoid over smoothing of test images.

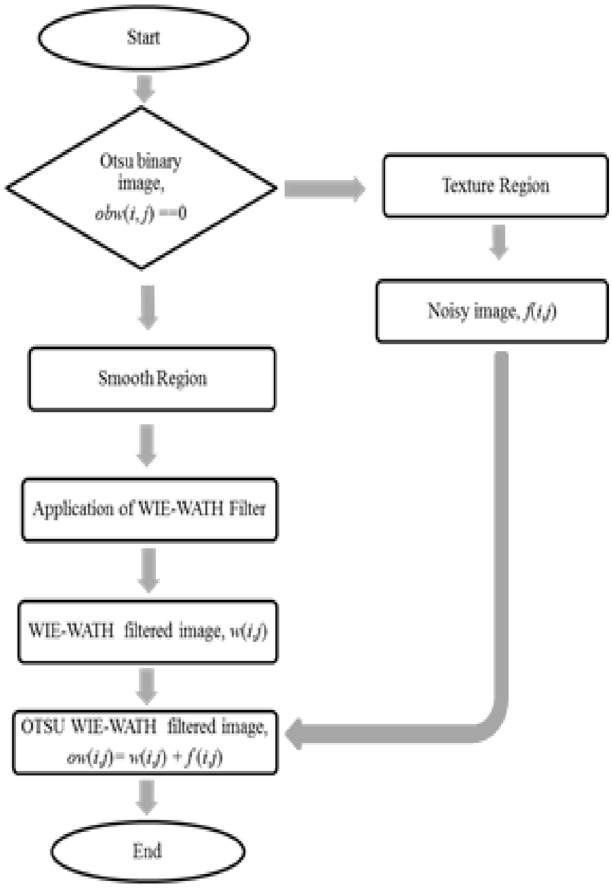

Figure 4: Flowchart for OTSU WIE-WATH filter

IV. Results and Analysis

This chapter discusses the results obtained from testing of different low light image filters using MATLAB software. The experiment was conducted to measure the effectiveness of the proposed filters in removing different levels of Poisson noise in low light condition digital images.

8 selected test images are kl.jpg (367×374), sarawak.jpg (599×442), firework.jpg (609×679), tapir.jpg (303×374), johor.jpg (375×500), masjid.jpg (800×600), arch.jpg (525×402) and beach.jpg (441×461). These test images are captured using digital single-lens reflex (DSLR) camera in low light condition and are chosen to represent different low light image characteristics for more precise analysis of proposed low light image filters. The kl.jpg, sarawak.jpg, firework.jpg and tapir.jpg images have more textures like edges and details. On the other hand, johor.jpg, masjid.jpg, arch.jpg and beach.jpg images have lower amount of edges and details.

There are 6 scales of Poisson noise chosen for the experiment which is then classified into 3 categories: 3 scales representing low level Poisson noise (1e7, 5e7 and 1e8), and 3 scales representing medium level Poisson noise (5e8, 1e9 and 5e9). The performances of proposed and existing filters that are applied on different test images corrupted by these 3 categories of Poisson noise are analyzed respectively. The Poisson noise in the test images are denoised by using proposed method, OTSU WIE-WATH Filter. The performance of proposed filter is also compared with 6 other conventional or previously developed denoising filters, which are the Kuwahara Filter [13], WIE-WATH Filter [8], KU-WATH Filter [7], OTSUHARA Filter [7], Bilateral Filter [4] and the combination of Bilateral Filter and Wavelet Threshold [6]. The performances of these filters are evaluated based on the Peak Signal to Noise Ratio (PSNR), Mean Squared Error (MSE), and visual effect inspection. This next part discusses on the suitable parameters required for proposed method, OTSU WIE-WATH Filter. There are three parameters to be considered which are *T1* parameter for *bwareopen* function of Otsu Threshold, Wiener factor, *ñ*, and Wiener mask size, *n*.

A. *Parameter Setting for OTSU WIE-WATH Filter: Otsu Threshold Parameter Setting*

For the Otsu Threshold, grayscale image threshold and *bwareopen* function need to be considered. As grayscale image changed to binary image while applying Otsu Threshold, the binary image has pixels with values 0 and 1 because grayscale image has default setting of [0 1]. Besides, the connected component threshold, *p* in *bwareopen* function is used for removing the connected components (objects) in image. It removes the connected objects fewer than the chosen *T1* parameter in image. According to previous study [7], *T1*=30 provides the best results in avoiding large amount of objects to be removed, thus preserving the image's fine details and edges. Therefore, this study uses *T1*=30 on the bwareopen function of Otsu Threshold.

B. *Parameter Setting for OTSU WIE-WATH Filter: Wiener Filter Parameter Setting*

This part discusses the parameter setting for Wiener Filter. There are two important parameter settings for Wiener Filter which are Wiener factor, *ñ* and Wiener mask size, *n*.

Wiener factor, *ñ* is the parameter used to decrease or increase estimated power of a noise used by the Wiener Filter. There are four ñ investigated which are 0.001, 0.01, 0.1 and 1 to identify which factor is the most suitable to apply for OTSU WIE-WATH Filter to obtain optimum PSNR and MSE performances for all test images. For OTSU WIE-WATH, these four *ñ* factors are applied on denoising the test images with two different levels of Poisson noise which are 1e7, 5e7 and1e8 (represent low noise test images) and 5e8, 1e9 and 5e9 (represent medium noise test images), respectively. The average PSNR and average MSE for these two test image sets for OTSU WIE-WATH Filter with different Wiener factors, *ñ* are analyzed respectively.

The calculation for average PSNR and average MSE are obtained by the following steps:

i. A test image is added with a level of Poisson noise and then filtered using OTSU WIE-WATH Filter with a level of Wiener factor, ñ. The PSNR value obtained is recorded.
ii. Step *i* is repeated for each test image, kl.jpg, sarawak.jpg, firework.jpg, tapir.jpg, johor.jpg, masjig.jpg, arch.jpg and beach.jpg test images, respectively, with Poisson noise level of 1e7, 5e7 and 1e8,respectively, for Wiener factors, ñ = 0.001, 0.01, 0.1 and 1, respectively.
iii. The PSNR values obtained from for each Poisson noise level is summed up and divided by 8 to obtain the average PSNR for all 8 test images with a Poisson noise scale. The calculated average PSNR value is recorded.
iv. The average PSNR values recorded are summed up and divided by 3 to obtain the total average PSNR for low level Poisson noise.
v. Steps *i* to *iv* are repeated by replacing PSNR with MSE to obtain the average MSE and total average MSE for 3 of the low Poisson noise scales.

Based on the observation from the experiments, with Wiener factors, *ñ* of 0.001, 0.01 and 0.1, the average PSNR and average MSE of all test images for low and medium noise levels perform better than *ñ* of 1. The performances of *ñ* = 0.001, 0.01 and 0.1 generate almost similar results, therefore *ñ* = 0.001 which performed slightly better for both low and medium noise levels is chosen.

There are three Wiener mask size, *n* investigated which are 3×3, 5×5 and 7×7. For the proposed filter OTSU WIE-WATH which is designed for effective noise removal in low and medium noise levels, the 3 mask sizes are applied on 6 Poisson noise scales: 3 scales representing low noise (1e7, 5e7 and 1e8) and 3 scales representing medium noise (5e8, 1e9 and 5e9). The average PSNR and average MSE of all 8 test images are analyzed respectively. The average PSNR and average MSE are obtained by the similar step for the calculation for average PSNR and average MSE in Part IV (*A*) for Wiener mask size, *n* = 3×3, 5×5 and 7×7, respectively.

It can be observed from the experiments that the Wiener mask setting of 3×3 is the most suitable to obtain the best average PSNR and average MSE performances for all test images of low and medium noise levels, thus *n* of 3×3 is chosen.

C. *Parameter Setting for Existing and Proposed Filters*

Table 1 shows the complete parameter settings of different filters applied for performance comparison of proposed methods with other conventional methods.

Table 1
Parameter Setting for Comparison Methods

Filter Name	Parameters	Settings
OTSU WIE-WATH	Threshold level	[0 1]
	T1	30
	Wiener factor, ñ	0.001
	Wiener mask size, n	3×3
	DWT decomposition level	2
Kuwahara [13]	Kuwahara mask size	3×3
WIE-WATH [8]	Wiener factor, ñ	0.1
	Wiener mask size, n	3×3
KU-WATH [7]	Kuwahara mask size	3×3
	DWT decomposition level	1
OTSUHARA [7]	Threshold level	[0 1]
	T1	30
	Kuwahara mask size	3×3
Bilateral (BL) [4]	*w*, window size	5
Bilateral Filter +Wavelet Threshold (BL+ WL) [6]	*w*, window size DWT Decomposition Level	5 1

D. *Lw and Medium Poisson Noise Denoising Performance*

This part discusses in detail on the low and medium noise removal performance of proposed filters, OTSU WIE-WATH Filter with other existing denoising filters which are Kuwahara Filter, WIE-WATH Filter, KU-WATH Filter, OTSUHARA Filter, Bilateral Filter, BL, and the combination of Bilateral Filter and Wavelet Threshold, BL+WL.

Poisson noise scales of 1e7, 5e7, and 1e8 which represent low level Poisson noise are utilized to analyse the performance of various denoising technique. 8 of the test images added with low level Poisson noise are denoised using different filters including proposed filters and existing filters. Conversely, Poisson noise scales of 5e8, 1e9, and 5e9 represents medium level Poisson noise. 8 of the test images added with medium level Poisson noise are also denoised using different filters including proposed filters and existing filters.

The filters performances are analyzed with two evaluation methods which are objective method and subjective method. Objective method is performance analysis method which can be represented by numbers or values. These methods included performance analysis in terms of the PSNR and MSE. On the other hand, subjective method used is visual effect inspection.

In this part, objective evaluation methods are done using the following procedures. The average PSNR and average MSE are obtained by the similar step for the calculation for average PSNR and average MSE in Part IV (*A*) for the OTSU WIE-WATH Filter, Kuwahara Filter, WIE-WATH Filter, KU-WATH Filter, OTSUHARA Filter, Bilateral Filter, BL and the combination of Bilateral Filter and Wavelet Threshold, BL+WL, respectively.

E. Comparisons of PSNR and MSE Performances

The resultant filters' performances in terms of PSNR on 8 of the low and medium Poisson noise corrupted test images are shown in Table 2, higher PSNR indicates better denoising performance. Table 2 shows that OTSU WIE-WATH Filter has the highest total average PSNR performances in denoising both low and medium noise levels test images with different image characteristics. For low noise removal, the total average PSNR of OTSU WIE-WATH Filter improved by 0.92dB when compared to OTSUHARA Filter and improved by 3.08dB when compared to WIE-WATH Filter. For medium noise removal, the total average PSNR of OTSU WIE-WATH Filter improved by 0.76dB when compared to OTSUHARA Filter and improved by 1.79dB when compared to WIE-WATH Filter.

Table 2
Total Average PSNR (+dB) Performance for Proposed and Existing Denoising Techniques

Denoising Techniques	Low Poisson Noise	Medium Poisson noise
OTSU WIE-WATH	81.82	80.17
Kuwahara	77.10	76.82
WIE-WATH	78.74	78.38
KU-WATH	76.82	76.67
OTSUHARA	80.91	79.41
Bilateral	79.10	78.95
BL+WL	77.30	77.24

The resultant filters' performances in terms of MSE on 8 of the low and medium Poisson noise corrupted test images are shown in Table 3, lower MSE indicates better denoising performance. Table 3 shows that OTSU WIE-WATH Filter has the lowest total average MSE performances in denoising both low and medium noise levels test images with different image characteristics. For low noise removal, the total average MSE of OTSU WIE-WATH Filter improved by 0.0025 when compared to OTSUHARA Filter and improved by 0.0094 when compared to WIE-WATH Filter. For medium noise removal, the total average MSE of OTSU WIE-WATH Filter improved by 0.0025 when compared to OTSUHARA Filter and improved by 0.0061 when compared to WIE-WATH Filter.

Table 3
Total Average MSE Performance for Proposed and Existing Denoising Techniques

Denoising Techniques	Low Poisson Noise	Medium Poisson Noise
OTSU WIE-WATH	0.0214	0.0258
Kuwahara	0.0377	0.0387
WIE-WATH	0.0308	0.0319
KU-WATH	0.0391	0.0396
OTSUHARA	0.0239	0.0283
Bilateral	0.0295	0.0299
BL+WL	0.0366	0.0368

F. Comparisons of Visual Effect for Low and Medium Poisson Noise Removal

The visual effects inspection is based on the observation using human eye-sight. The physical characteristic such as edges, fine details and quantity of noises in processed test images is observed. There are 10 images obtained by processing a single test image namely Original Image, Noisy Image, OTSU WIE-WATH Filtered Image, Kuwahara Filtered Image, WIE-WATH Filtered Image, KU-WATH Filtered Image, OTSUHARA Filtered Image, Bilateral Filtered Image and the Bilateral+ Wavelet Threshold Filtered Image. Different test images with Poisson noise scales of 1e7, 5e7 and 1e8 (represent low Poisson noise test images) and 5e8, 1e9 and 5e9 (represent low Poisson noise test images) are utilized for visual effect inspection.

As an example of the result, Figure 5 in Appendix provides the denoising effects for medium level Poisson noise. The edges and fine details in texture regions of noisy image remained almost the same as the original image. The noises in image smooth region are expected to be removed thoroughly after application of proposed OTSU WIE-WATH Filter. It is observed that OTSU WIE-WATH filtered image and WIE-WATH filtered image are almost the same as the original image. These images have all noisy pixels in the smooth regions removed and well preserve fine edges and details in texture region. OTSUHARA filtered image also has well preserve texture region but there are some noisy pixels in smooth region that never remove thoroughly. On the other hand, WIE-WATH and KU-WATH filtered images have over-smoothed texture regions. The over-smoothed effect is more serious in texture region of Bilateral and Bilateral+Wavelet filtered images which give a blurred visual effect. Thus, it is proved that OTSU WIE-WATH Filter has the best visual inspections, it provides well noise removal and edges and fine details preservation in low and medium noise levels.

The subjective analysis method is visual effect inspection. This method is utilized while analyzing the performance of different filters on 8 test images. First of all, the results obtained in terms of PSNR showed that OTSU WIE-WATH Filter gives 3.08dB and 1.79dB improvement for low and medium level Poisson noise respectively when compared to WIE-WATH Filter. When compared to OTSUHARA Filter which is an existing filter ideal for low and medium noise, OTSU WIE-WATH Filter gives 0.92dB increment for low level Poisson noise and 0.76dB increment for medium level Poisson noise. Results obtained in terms of MSE showed that OTSU WIE-WATH Filter gives 0.0094 and 0.0061 improvement for low and medium level Poisson noise respectively when compared to WIE-WATH Filter. When compared to OTSUHARA Filter, OTSU WIE-WATH Filter gives 0.0177 decrement for low level Poisson noise and 0.0025 decrement for medium level Poisson noise. For visual effect inspection, OTSU WIE-WATH filtered images for low and medium level Poisson noise are clearer and almost similar to original images with the edges and details well-preserved. The edges and details preserved better in the texture regions and more noise is removed in smooth regions of the filtered images.

(a) Original image

(b) Noisy image (Medium Noise, 5e9)

(c) OTSU WIE-WATH filtered image [PSNR: 77.435, MSE: 0.0344]

(d) Kuwahara filtered image [PSNR: 72.7673, MSE: 0.0589]

(e) WIE-WATH filtered image [PSNR: 75.3447, MSE: 0.0438]

(f) KU-WATH filtered image [PSNR: 72.4438, MSE: 0.0611]

(g) OTSUHARA filtered image [PSNR: 76.5954, MSE: 0.0379]

(h) Bilateral filtered image [PSNR: 77.3644, MSE: 0.0347]

(i) Bilateral+Wavelet Filtered Image [PSNR: 74.3428, MSE: 0.0491]

Figure 5: Visual effect for denoising firework.jpg corrupted by 5e9 Medium Poisson Noise

V. Conclusion

The study aims to develop effective denoising techniques for Poisson noise removal in low light condition digital images. This study proposed a denoising technique namely OTSU WIE-WATH Filter. The filter is specially designed for effective low and medium Poisson noise removal. Based on the results, proposed OTSU WIE-WATH Filter has better performance in terms of the PSNR(average of 80.995 dB) and MSE(average of 0.0236), as well as visual effects compared to other techniques analyzed for both levels of Poisson noise in test images.

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