An Improved Guided Filtering Algorithm for Polarized Images by Using LOG Operator

Le Zhan and Jiajia Chen*
Nanjing University of Aeronautics and Astronautics, Nanjing, China
*Corresponding author email: jiajia_chen@nuaa.edu.cn

***Abstract*—Guided image filter (GIF) is a commonly adopted local filter in image processing and computer vision, due to its edge-preserving property and low complexity. However, GIF may suffer from halo artifacts. In this paper, we present an improved guided filtering algorithm by using Laplacian-of-Gaussian (LOG) operator, which is dedicated to division-of-focal-plane (DoFP) polarization images to reduce the edge halo artifacts. By calculating the magnitude response of the LOG operator in the local window, the initial regularization parameter becomes self-adaptive to the values of the smooth area and edge area of the image. It can highlight the difference between edge pixels and the pixels in flat areas to show more details, especially at the edge. Experimental results demonstrate that the proposed algorithm performs better than the reference method in terms of both visual effect and root mean square error (RMSE). Especially for degree of linear polarization (DoLP) images, the RMSE has been significantly reduced by around 88%. In addition, the proposed filter made these improvements without computational overhead.**

Keywords—guided image filter, Laplacian-of-Gaussian (LOG) operator, polarization image

I. Introduction

In addition to the traditional imaging technology, polarization imaging is a new technology, which captures the polarization property of the object. Polarization can convey information about the transverse electric field orientation, through which we can accurately extract the relevant information of the target.

The emerging division-of-focal-plane polarimeter (DoFP) uses the integration of micro-optical polarization elements to form micro-polarizer array, very well similar the color filter array (CFA) directly has been realized [1], as shown in Fig. 1. The sensor is arranged in a 2×2 periodic pattern, named as one super-pixel. Each single-pixel contains the polarized light at only one of four different orientations: 0°, 45°, 90° and 135°. Although sensors can record all the polarization information of an object in a single frame, they are inevitably affected by instantaneous field of view (IFOV) error [2]. In order to address the issue, interpolation algorithms have been proposed to restore the missing polarization information at each pixel. The interpolation algorithm for a DoFP polarimeter is using intensity correlation [3].

Guided image filtering is one of the fast edge-preserving smoothing filters, which plays an important role in image enhancement. The edge-preserving smoothing algorithms can be divided into two categories: global optimization based and

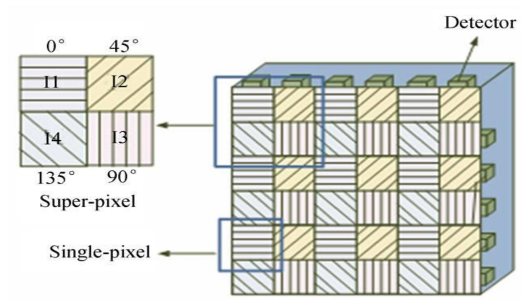


Fig. 1.A micro-polarizer array of a DoFP polarimeter with four polarization orientations.

local filter based. The global optimization based algorithms include total variation (TV) [5], weighted least squares (WLS) [6], fast weighted least squares (FWLS) [7], and *L*0 norm gradient minimization [8], which usually leads to better results than others. The other category uses local filters to perform the filtering, including median filter [9], bilateral filter (BLF) [10] and guided image filter (GIF) [11]. Median filter is one commonly used image-denoising filter, however, it may lose effective information, which causes the image discontinuity. In order to compensate this defect, in [12], adaptive median filter (AMF) adaptively adopts the adjustment of sliding window length, which can effectively denoise and protect the signal details. In addition, bilateral filtering (BLF) [10] has good characteristics of edge-preserving and denoising, but the protection of high frequency details is not effective. As one of the fastest edge-preserving smoothing filters, Guided image filter (GIF) [11] can compute more efficiently and exactly. Therefore, it is widely used in denoising, smoothening, High-Dynamic Range Imaging (HDR) and other applications. The main idea is using a linear transformation to compute the pixel values in a window. Different from other algorithms, GIF computes the output image by considering the structure of a guidance image. However, this technique has a drawback that it may create halos near some edges [11], which reduce the visual quality of the output images. Moreover, in [13], a weighted GIF (WGIF) is introduced with a zeroth-order constrain to make the edge preserved better and lessen the halo artifacts of the GIF. However, these filters still cannot preserve edges well in some details.

To address these challenges, in this paper, we propose a new guided filtering algorithm for DoFP image, by using Laplacian-of-Gaussian (LOG) operator. Marr and Hildreth firstly proposed the LOG operator in 1980 [14]. It combines

Gaussian smoothing and Laplacian differentials, and reduces the sensitivity of the Laplacian operator to noise. In the proposed algorithm, LOG operator is used to calculate the weight, and we adopt weighted guided filtering to process the image, so as to ensure the image resolution and highlight the edge details. In addition, by combining the information of the pixels from different regions, we use an adaptive normalization factor in the proposed weighted guided filtering. The experimental results show that the proposed algorithm can effectively eliminate the halos near the edge, and improve the image clarity. The proposed GIF algorithm significantly enhances the characteristic of edge-preserving by using LOG operator.

II. Related Works

A. Linear polarization calculation

A DoFP polarization sensor with the structure in Fig.1 captures both the intensity and polarization information of a scene. The intensity is measured by the light through θ ($\theta = 0°$, 45°, 90°, 135°) polarization filter. The standard way to represent light polarization is by using first three Stokes parameters to describe the polarization properties of light [15].

$$S_0 = \left(I_{0^\circ} + I_{45^\circ} + I_{90^\circ} + I_{135^\circ}\right) \tag{1}$$

$$S_1 = I_{0^\circ} - I_{90^\circ} \tag{2}$$

$$S_2 = I_{45^\circ} - I_{135^\circ} \tag{3}$$

where S_0 is the total intensity of the light, S_1 and S_2 describe the amount of linear polarization. To observe polarization, two typical properties that describe the degree of linear polarization (DoLP) and the angle of polarization (AoP) [15], are calculated by:

$$DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0} \tag{4}$$

$$AoP = \frac{1}{2}\arctan\left(\frac{S_2}{S_1}\right) \tag{5}$$

B. GIF

GIF is a local linear model to smoothen the image while maintaining its edge details. Guidance image is denoted as I and the image to be filtered is p. We assume that q is a linear transform of I in a window w_k centered at the pixel k:

$$q_i = a_k I_i + b_k, \forall i \in w_k \tag{6}$$

where a_k and b_k are two constants in the window w_k , and w_k is a square of radius r. To determine a_k and b_k, we derive the solution to (6) that minimizes the difference between the output q and the filter input p. Specifically, we minimize the following cost function in the window:

$$\mathrm{E}\left(a_k, b_k\right) = \sum\nolimits_{i \in w_k}\left(\left(a_k I_i + b_k - p_i\right)^2 + \varepsilon a_k^2\right) \tag{7}$$

Here ε is a regularization parameter. The optimal values of a_k and b_k can be derived by the following linear regression:

$$a_k = \frac{\frac{1}{|w_k|}\sum\nolimits_{i \in w_k} I_i p_i - \mu_k \overline{p_k}}{\sigma_k^2 + \varepsilon} \tag{8}$$

$$b_k = \overline{p_k} - a_k \mu_k \tag{9}$$

Here, μ and σ_k^2 are the mean and variance of I in w_k, where $|w_k|$ is the number of pixels in w_k. $\overline{p_k} = \frac{1}{|w_k|}\sum\nolimits_{i \in w_k} p_i$ and it is the mean of p in w_k.

GIF can effectively avoid gradient inversion artifacts. However, when smoothening the edge using GIF in [11], the halo is inevitable. To solve this problem, Li et al. [13] firstly proposed the concept of weighted guided filtering (WGIF) and calculated the edge weight by using local variance in a 3×3 window. The edge-weighting factor $\Gamma_I(i)$ is calculated as follows:

$$\Gamma_I(i) = \frac{1}{N}\sum_{i'=1}^{N}\frac{\sigma_{I,1}^2(i) + \lambda}{\sigma_{I,1}^2(i') + \lambda} \tag{10}$$

$\sigma_{I,1}^2(i)$ is the variance of I in $w_1(i)$, which is a square window centered at a pixel i with radius 1. λ is a small constant and is selected as $(0.001 \times R)^2$, where R is the range of grayscale value. N is the total number of pixels in the image. With (10), the new minimum cost function to replace (7) is:

$$\mathrm{E}' = \sum_{i \in w_k}\left[\left(a_k + b_k - p_i\right)^2 + \frac{\varepsilon}{\Gamma_I(i)} a_k^2\right] \tag{11}$$

C . Laplacian-of-Gaussian (LOG) operator

LOG operator is regarded as one of the best edge detection operators, which approximates a Gaussian-smoothing filter to smoothen the original image for the maximum denoise suppression [14]. Subsequently, it extracts the edges of the smoothened image to apply a Laplacian.

The Laplacian operator of an image with pixel intensity values $f(x, y)$ can be expressed as:

$$\mathrm{L}\left(f(x,y)\right) = \frac{\partial^2 f(x,y)}{\partial x^2} + \frac{\partial^2 f(x,y)}{\partial y^2} \tag{12}$$

The expression of 2-D Gaussian operator is:

$$\mathrm{G}(x,y) = \frac{1}{2\pi\sigma^2}\exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right) \tag{13}$$

The value of σ is a standard deviation of the Gaussian function. However, the Laplacian operator is sensitive to noise. To address this issue, the image is firstly smoothened by Gaussian operator and is then detected for the edge by Laplacian operator. Therefore, this process can be expressed by (14) as:

$$\nabla^2\left(\mathrm{G}(x,y) * f(x,y)\right) = \left(\nabla^2\mathrm{G}(x,y) * f(x,y)\right) \tag{14}$$

$\nabla^2\mathrm{G}(x,y)$ is the LOG operator with zero-mean and Gaussian standard deviation σ, as the form:

$$\nabla^2\mathrm{G}(x,y) = -\frac{1}{\pi\sigma^4}\left(1 - \frac{x^2 + y^2}{2\sigma^2}\right)\exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right) \tag{15}$$

With LOG operator, we can detect the edge of the image by the convolution result of the second derivative trajectory of the zero intersection. LOG operator eliminates all the image intensities, which change less than σ through image smoothing. Its second-order differential is non-directional, so it can save computational effort. Moreover, it has good edge continuity, and can extract edge points with low contrast, so we chose to use LOG operator in our method.

III. The Proposed Algorithm

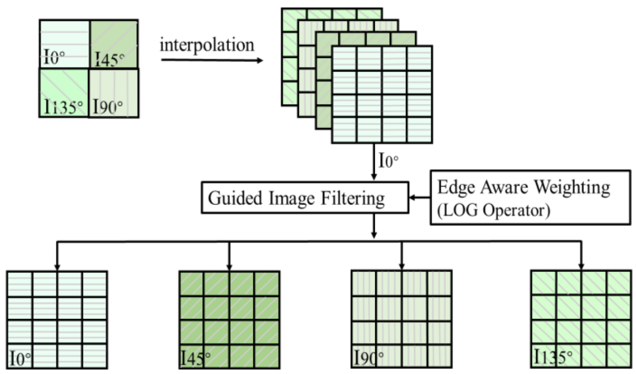


Fig. 2. Flow chart of the algorithm

In this section, we present the improved guided filtering algorithm by using LOG operator to DoFP image, as shown in Fig. 2. The objective is to improve the quality of polarization image such as keeping clearer edge details. Primarily, with the four sub-images ($I_{0°}$, $I_{45°}$, $I_{90°}$, $I_{135°}$), we adopt the interpolation method in [3] to enhance spatial resolution and reduce IFoV errors in DoFP image. After this, we apply the proposed guided filtering by using LOG operator on the interpolated images.

A. A new edge-aware weighting

Inspired by the edge-preserving smoothening technique WGIF [13], the proposed filter uses absolute amplitude of the local LOG operator instead of the variance of guidance image I in w_k. The new edge-aware weighting factor $\Gamma_G(i)$ is defined as follows:

$$\Gamma_G(i) = \frac{1}{N}\sum_{i'=1}^{N}\frac{|\mathrm{LOG}(i)| + \lambda_{\mathrm{LOG}}}{|\mathrm{LOG}(i')| + \lambda_{\mathrm{LOG}}} \tag{16}$$

where the function LOG is Laplacian-of-Gaussian operator, i and i' represent the center pixel and all pixels of the guidance image respectively. λ_{LOG} is a weighted edge regularization parameter which is a small constant.

Since λ used in WGIF [13] is fixed, which results in the texture differences between pixels in different windows not being considered. Moreover, the value of λ is directly related to the local variance in w_k, which can reflect the edge information to some extent. However, regions with large variances do not correspond to regions with strong edges. To address this issue, a new regularization parameter λ_{LOG} is calculated in the weighting. We found that the value of λ_{LOG} is taken from the self-adaptation of the LOG image, which makes it more robust. Therefore, we choose 0.01 times the maximum absolute value of $\mathrm{LOG}(i')$ as the value of λ_{LOG}. In our method, the size of the LOG operator is 9×9 and the variance is 1.5.

B. The proposed filter

With $\Gamma_G(i)$ calculated via (18), the cost function E', the optimized values a'_k and b'_k can be calculated from (17) to (19), as:

$$E' = \sum_{i\in w_k}\left[\left(a'_k + b'_k - p_i\right)^2 + \frac{\varepsilon}{\Gamma_G(i)} a'^2_k\right] \tag{17}$$

$$a'_k = \frac{\frac{1}{|w_k|}\sum_{i\in w_k} I_i p_i - \mu_k \overline{p_k}}{\sigma_k^2 + \frac{\varepsilon}{\Gamma_G(i)}} \tag{18}$$

$$b'_k = \overline{p_k} - a'_k \mu_k \tag{19}$$

Compared with the original solution of guided filtering, the edge-weighted factor of the proposed filter is adjusted, therefore a'_k is more stable while the complexity of the algorithm has not changed. The complexity of the proposed filter is still $O(N)$ as GIF [11], where N is the number of pixels. In addition, the edge can be better preserved.

Mathematically, the final value of q_i can be calculated by (20), as:

$$q_i = \overline{a_i} I_i + \overline{b_i} \tag{20}$$

where $\overline{a_i}$ and $\overline{b_i}$ are respectively the means of a'_k and b'_k, calculate within w_k, as:

$$\overline{a_i} = \frac{1}{|w_k|}\sum_{k\forall i\in w_k} a'_k \tag{21}$$

$$\overline{b_i} = \frac{1}{|w_k|}\sum_{k\forall i\in w_k} b'_k \tag{22}$$

and $|w_k|$ is the cardinality of w_k.

C. Analysis and summary of the proposed filter

As summarized by the flow chart shown in Fig. 2, the four interpolated images are taken as the input images to subsequent optimization processes. Subsequently, the proposed filter could significantly improve the overall edge-preserving quality. The LOG operator can take the zero-crossing points that are consistent with edges at different scales, and detect the smallest edges in the image.

The LOG operator is a second-order edge detection operator, which has larger absolute amplitude at the edge pixel. Therefore, the value of $\Gamma_G(i)$ at edge is larger than 1, whereas in the smooth area, it is smaller than 1 [16]. The image based on variance shows less details and is more blur, while the one based on LOG operator shows more details, especially at the edges. Since the value of ε used in GIF [11] for the whole image is fixed, which cannot reflect the texture differences in each region. At the same time, larger ε causes blurrier edge information. Therefore, this paper uses the characteristics of the LOG operator, including good edge continuity and the ability to extract edge points and regions with weaker contrast. In this case, $\varepsilon/\Gamma_G(i)$ becomes adaptive. Moreover, the proposed filter uses the intensity information of four channels of the polarization image to distinguish edge and texture details, so that the self-adaptive weighting factor has different values in different regions, which can better maintain the image information.

IV. Experimental Results

To analyze the effectiveness of the proposed algorithm, we use FLIR BFS-U3-51S5P-C camera to capture the DoFP images, which are with a spatial resolution of 1280×2448 and a grey-level of 8-bit. They are separated into four polarization channels that are distributed every 45° from 0° to 135°. After interpolation, we apply the proposed guided filtering algorithm using LOG operator. We evaluate the performance by comparing the filtered images with the true images. Visual comparisons and quantitative comparison for reconstruction errors are performed.

A. Image visual comparison

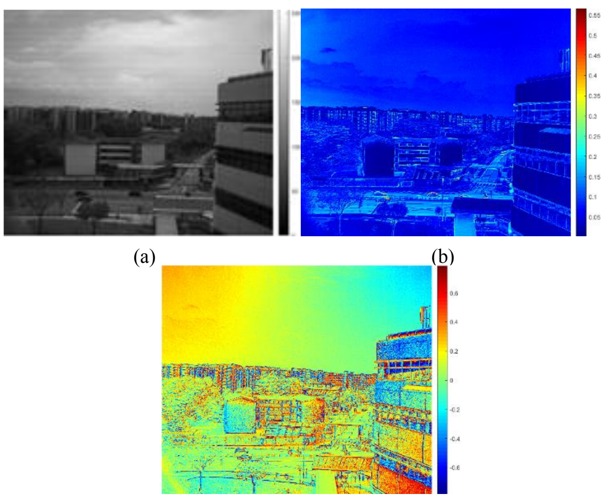
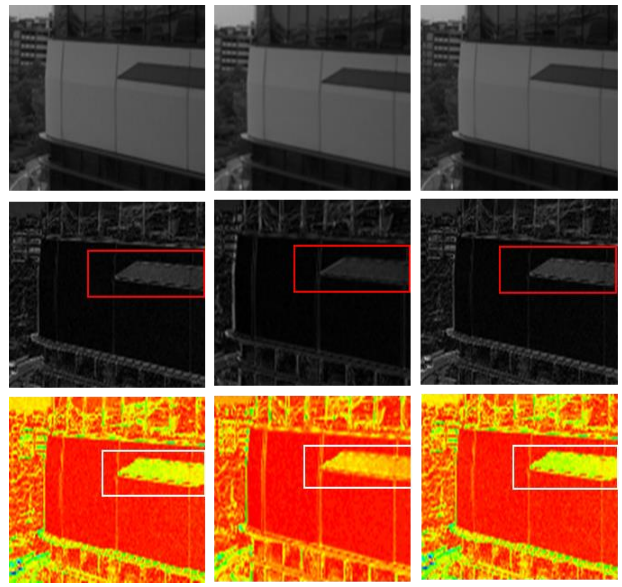


Fig. 3. The high-resolution images: (a) Intensity, (b) DoLP, (c) AoP

The intensity, DoLP and AoP of the testing polarization images are shown in Fig. 3. DoLP values are lower in the blue areas and higher at the edge, with the values goes up even higher in some very detailed regions. AoP values are low, medium, and high in the blue, green and red areas, respectively. We use these images to match with the true image, and explore the characteristics of polarization.

The true polarization images, which are used to visually compare the reconstruction accuracy by different methods, are presented in Fig. 4 first column. The second and third columns show the images that are reconstructed by intensity correlation interpolation method [3] and the proposed guided filtering, respectively. The first row presents intensity images and the second row presents DoLP images. The marked red rectangle regions in the DoLP images are processed using Hue Saturation Value (HSV) false color model and presented in the last row. It can be observed that the edges in the intensity image are smoothened, and the artifacts appear in the DoLP image due to large error introduced by interpolation method. These artifacts are obvious compared with the ground truth image, especially in DoLP image. On the other hand, the images by our method have the artifacts minimized and edges well preserved. In addition, our method generates the intensity images which is the closest to the ground truth. The HSV false color model is presented in the last row, so we can find that the images processed by our method have higher saturation and brightness in the edge area than [3]. Similar to the comparison above, the result of our method in HSV is the closest to the true polarization image. In conclusion, our proposed method can achieve better visual effects compared with [3]. In addition, our method is also better in preserving the edges.



(a) (b) (c)

Fig. 4. Visual comparison of image. (a) True polarization, (b) Interpolation method, (c) Our method.

B. Quantitative comparison

In addition to subjective evaluation, we introduce a quantitative comparison. We employ root mean square error (RMSE) to evaluate the accuracy of the different methods. The formula of RMSE is described by (23):

$$\mathrm{RMSE}=\sqrt{\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(I_{true}(i,j)-I_{img}(i,j)\right)^{2}} \tag{23}$$

where $I_{ture}(i,j)$ and $I_{img}(i,j)$ are the values of the true image and the processed image, respectively. M and N are the numbers of rows and columns in the image array, respectively. Ten polarization images are used as the testing images, which are presented in Fig. 5.

Fig. 5. Polarization images used

The average RMSE results of all 10 scenes are listed in Table 1, where the better results are highlighted in bold. The proposed algorithm always has the lower RMSE compared with [3]. For $I_{0°}$ to $I_{135°}$, the RMSE reductions are about 80%.

For S_0 and DoLP, the reductions are around 67% and 88%, respectively. These improvements are made by using LOG operator in our method to detect the difference between pixels in the flat area and the edge area. These differences are used to distinguish regions of the image. This makes the edges to be preserved rather than smoothened, so the details of the image are better protected. Meanwhile, this can reduce the image quality degradation during the processing. This comparison shows that our method can process polarization images with the significantly higher accuracy than the algorithm in [3].

Table 1. The comparison of average RMSE of 10 scenes

	Intensity correlation-based [3]	Our method
I_{0°	3.65336	**0.72613**
I_{45°	3.75637	**0.760065**
I_{90°	4.00038	**0.795687**
I_{135°	3.98373	**0.805338**
S_0	4.08759	**1.33595**
DoLP	0.031946	**0.0039186**

V. Conclusion

In this paper, a new local adaptive weighted guided filtering method based on LOG operator is presented to process polarization images. The proposed method uses the characteristics of LOG operator to detect the difference between the pixels in and outside the edge area. With it, the proposed weighted guided filtering is adaptive to the input image, and therefore can perform better in edges preservation and halo artifacts elimination. In addition, the complexity of our method is $O(N)$ which is same as the original GIF. The experimental results show that the proposed algorithm has a better visual effect and lower RMSE than the previous results.

Acknowledgement

This research was supported by Jiangsu Natural Science Foundation under grant 1004-PAC19009. This research was also supported by the Open Foundation of Graduate Innovation Base (Laboratory) of Nanjing University of Aeronautics and Astronautics under grant kfjj20200410.

Reference

[1] A. Abubakar, et al., “A block-matching and 3-D filtering algorithm for gaussian noise in DoFP polarization images,” *IEEE Sensors Journal*, vol. 18, no. 18, pp. 7429-7435, Sep. 2018.

[2] B. M. Ratliff, C. F. LaCasse, and J. S. Tyo, “Interpolation strategies for reducing IFOV artifacts in microgrid polarimeter imagery,” *Optics Express*, vol. 17, no. 11, pp. 9112-9125, Jun. 2009.

[3] J. Zhang, et al., “Image interpolation for division of focal plane polarimeters with intensity correlation,” *Optics Express*, vol. 24, no. 18, pp. 20799-20807, Sep. 2016.

[4] N. Li, et al., “Demosaicking DoFP images using Newton's polynomial interpolation and polarization difference model,” *Optics Express*, vol. 27, no. 2, pp. 1376-1391, Jan. 2019.

[5] C. Jin, and N. Luan, “image denoising based on total variation and weighting function,” *Electronic Measurement Tenology*, vol. 41,no. 7, pp. 58-63, Apr. 2018.

[6] H. Li, L. Yun, and Y. Gao, “Fog image enhancement algorithm based on boundary constraint weighted least squares filtering,” *Chinese Journal of Lasers*, vol. 46, no. 3, pp. 1-9, Mar. 2019.

[7] D. Min, et al., “Fast global image smoothing based on weighted least squares,” *IEEE Trans. Image Processing*, vol. 23, no. 12, pp. 5638-5653, Dec. 2014.

[8] L. Xu, C. Lu, Y. Xu, and J. Jia, “Image smoothing via L0 gradient minimization,” *ACM Trans. on Graphics*, vol. 30, no. 6, pp. 1-12, Dec. 2011.

[9] R. C. Gonzalez, and R. E. Woods, *Digital Image Processing*, 4th Edition, Pearson, Mar. 2017.

[10] X. Zhang, L. Dai, “Fast bilateral filtering,” *Electronics Letters*, vol. 55, no. 5, pp. 258-260, Mar. 2019.

[11] K. He, J. Sun, and X. Tang, “Guided image filtering,” *IEEE Trans. Pattern Anal. Mach. Intell*, vol. 35, no. 6, pp. 1397-1409, Jun. 2013.

[12] K. Venkatachalam and E. Mohan, “A novel algorithm for image denoising using modified aadaptive median filter,” *Research Journal of Applied Sciences, Engineering and Technology*, vol.10, no. 4, pp. 373-375, Jun. 2015.

[13] Z. Li, et al., “Weighted guided image filtering,” *IEEE Trans. on Image Processing*, vol. 24, no. 1, pp. 120-129, Jan. 2015.

[14] F. Zhao and C.J.S. Desilva, “Use of the Laplacian of Gaussian operator in prostate ultrasound image processing,” *in Proc. IEEE Engineering in Medicine and Biology Conf*, vol. 20, no. 2, pp. 812-815, Jan. 1998.

[15] Y. Zhao, et al., *Multi-band polarization imaging and applications*, Springer Berlin heidelberg, Oct. 2016.

[16] P. Long, and H. Lu, “Weighted guided image filtering algorithm using Laplacian-of-Gaussian edge detector,” *Journal of Computer Applications*, vol. 35, no. 5, pp. 2661-2665, Sep. 2015.