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Implementation and Validation of Visual and Infrared Image Fusion Techniques in C#.NET Environment

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Abstract: This paper presents the implementation of image fusion techniques by means of an image fusion application "C#ImFuse", developed in C#.NET. C# programming language is a simple, type-safe, object-oriented language that allows programmers to build a variety of applications. C#ImFuse application implements four fusion methods viz., Alpha Blending (AB), Principle Component Analysis (PCA), Laplacian Pyramid (LP), and Discrete Wavelet Transform (DWT) for a visual and a thermal image (still images) and for real-time images of the Enhanced Vision System (EVS). The performance of these fusion techniques is evaluated using fusion performance metrics. LP based image fusion technique proved to provide better fusion when compared to the other techniques. Source code is provided so that the reader can understand the techniques and use for his research work (pl. contact by emails).

Keywords: Image fusion in C#; image processing; Laplacian Pyramid; wavelets

1. Introduction

Image Fusion is a process of combining the features of two or more images of a scene into a single image that is more informative and is suitable for visual perception or computer processing. Fusion of images can be achieved using various fusion methods viz., pixel by pixel averaging [1], principal component analysis [1], wavelets [1], discrete cosine transform [2], Laplacian pyramid [3] etc. When the images to be fused are in the same scene but have different Field of View (FOV), image registration is required. In this paper, a visual image and a thermal image are considered for fusion. While fusing EO image (colour image of RGB format) and IR image (a gray image), the fusion has to be taken place at intensity level, as this preserves the colour information of EO image. Therefore, the EO image is to be converted from RGB to HSI (Hue Saturation Intensity) before performing the fusion. After the fusion of Intensity component (I) of EO image and IR image, an H and S component of EO image have to be added to the fused image and is to be converted to RGB to get back the colour information. Figure 1 describes the steps involved in fusion of still images. Real-Time image fusion is performed on Electro-optical (EO) and Infrared (IR) images obtained from Enhanced Vision System (EVS).

The application development for implementing the fusion techniques is done in C#, a .NET programming language. It is a high-level language and is very easy to work with, compared to the low-level C++. C# is best-suited language for software and web applications development in windows platform[4].Therefore, C# is considered in this study to develop "C#ImFuse".

1.1RGB and HSI Colour Models

RGB and HSI are colour models of an image. In RGB model, colours are represented by the amount of red light, green light, and blue light reflected from a scene and they are represented numerically with a set of three numbers, each of which ranges from 0 to 255. White has the highest RGB value of (255, 255, 255) and black has the lowest value of (0, 0, 0). HSI colour model represents every colour with their Hue, Saturation and Intensity. Hue of a colour describes the colour itself in the form of an angle between [0^0,360^0]. 0^0 means red, 120^0means green, 240^0 means blue, 60^0 is yellow and 300^0 is magenta. Saturation component gives a measure of dilution of a colour with white colour. The range of S component is [0, 1]. Intensity is the overall lightness or brightness of the colour, defined numerically as the average of the equivalent RGB values [5].

1.2 RGB to HSI Conversion

Conversion of an image from RGB to HSI can be achieved in this application by using EmguCV command ‘CvInvoke.CvtColor()’, and parameter ‘ColorConversion.Rgb2HsvFull’ [6].

1.3HSI to RGB Conversion

HSI to RGB conversion can be performed using the same command, ‘CvInvoke.CvtColor()’but parameter changes to ‘ColorConversion.Hsv2RgbFull’[6].

2. Image Fusion Techniques

Four-fusion techniques viz., Alpha Blending, Laplacian pyramid, Principal Component Analysis and Discrete Wavelet Transform are implemented in the Fusion Application. The following sections give a brief description of these techniques.

2.1 Alpha Blending

Alpha blending is a process of combining an image with its background. The level of transparency of background and foreground images is controlled by α and $(1-\alpha)$respectively. Eq. (1) governs fusion of images in Alpha Blending.

$$I_f(x,y) = \alpha * I_1(x,y) + (1-\alpha) * I_2(x,y) \qquad (1)$$

Where $0 \le \alpha \le 1$, I_f - fused image,

I_1 and I_2 - input images to be fused

(x, y) - Pixel index

Figure 2 shows the information flow diagram of image fusion using Alpha Blending. Either of the EO and IR images can be taken as the background image. In this study, EO image is taken as background image as it contains colour information as well as higher FOV. The transparency of background image is decided by α given by the user and the transparency of foreground image is equal to $(1-\alpha)$. Alpha blending is done by using ‘CvInvoke.AddWeighted()’, anEmguCV function [6], which takes α and $(1-\alpha)$ as parameters. α varies from 0 to 1 and when it is 0.5, it results in pixel by pixel averaging of EO and IR images.

2.2 Principal Component Analysis (PCA)

PCA technique is similar to Alpha Blending; the only difference is in determining the weightage to be given to each input image. The weightage is determined dynamically in PCA, whereas the user has to give the weightage (i.e. transparency) in Alpha Blending. PCA technique determines the weightage by calculating the Eigen values from the Eigen vectors from the image matrices. The information flow diagram of PCA-based image fusion algorithm is shown in Figure3. The images to be fused, $I_1(x, y)$ and $I_2(x, y)$ are arranged in two column vectors and their empirical means are subtracted. The resulting vector has a dimension $N \times 2$, where N is length of each image vector. Eigen vector and Eigen values for the resulting vector are computed and the eigenvectors corresponding to the larger eigenvalue are obtained. The normalized components P_1 and P_2 (i.e., $P_1 + P_2 = 1$) are computed from the obtained eigenvector [1]. The Eigen values are computed using the function “CvInvoke.Eigen()” [6].The fused image is:

$$I_f(x,y) = P_1 I_1(x,y) + P_2 I_2(x,y) \qquad (2)$$

2.3 Laplacian Pyramid

Image pyramid is a representation of an image in multiple scales. It is constructed by performing repeated smoothing and subsampling on the image. It is used to extract the features of interest, attenuate noise, reduce redundancy, enhance the image and for efficient coding.

There are two kinds of image pyramids. Gaussian pyramid, which is constructed by smoothing the image with an appropriate filter and then subsampling it by a scaling factor of ‘2’ repeatedly. Gaussian pyramid is an example for low pass image pyramids.

$$I_{dk} = g * I_k \qquad (3)$$

Here, g is the Gaussian convolution kernel, I_k is input image of k^{th} level of Gaussian pyramid and I_{dk} is the down sampled image of k^{th} level. The other kind is the Laplacian pyramid, which is a band pass pyramid, constructed by taking the difference between the adjacent levels of image pyramid. Laplacian pyramids computed as the difference between the original image and the low pass filtered image.

$$I_{Lk} = I_K - I_{uk} \qquad (4)$$

I_{Lk} is the Laplacian image of k^{th} level [1].

$$\text{Where} \quad I_{uk}(x,y) = \begin{cases} I_{dk}(x,y) & x, y = 1,3,5,\ldots \\ 0 & otherwise \end{cases} \qquad (5)$$

Laplacian based image fusion involves pyramid construction and image fusion. Laplacian pyramid is constructed for both EO and IR images from their respective Gaussian pyramids. This is done using the functions “CvInvoke.PyrDown()” and “CvInvoke.PyrUp()” [6]. Figure 4 shows the Laplacian pyramid based image fusion architecture. Coarse level (final level images obtained after decomposition) images of Gaussian pyramids of both EO and IR images are averaged (pixel by pixel). The resultant image is up-sampled and added with the maximum image (between EO and IR) of Laplacian pyramid in the immediate intermediate level. This is repeated until it reaches the fine level (original image) image of Gaussian pyramid.

2.4 Discrete Wavelet Transform (DWT)

Wavelet transform is a superset of Fourier transform. In Fourier theory, signal is decomposed into sine and cosines and in wavelet transform, the signal is projected on a set of wavelet functions. While Fourier transform provides good resolution in frequency domain, wavelet transform provides good resolution in both frequency and time domains. DWT uses a discrete set of wavelet scales and translation and it decomposes the signal into mutually orthogonal set of wavelets.

In DWT, the dilation factor is $a = 2^m$ and translation factor is $b = n2^m$ where m and n are integers. Wavelet transform of a 1-D signal f(x) is defined as:

$$W_{a,b}(f(x)) = \int_{x=-\infty}^{\infty} f(x)\psi_{a,b}(x)dx \tag{6}$$

Scaling function describes the scaling properties and the wavelets are constructed using it. The translation and dilation of mother wavelet is defined as:

$$\psi_{a,b}(x,y) = \frac{1}{\sqrt{a}}\psi\left(\frac{x-b}{a}\right) \tag{7}$$

Wavelet separately filters and down-samples the 2-D data (image) in horizontal and vertical directions. The input image $I(x,y)$ is filtered by low pass filter and high pass filter in horizontal direction and then down-sampled by a factor of two to create coefficient matrices $IL(x,y)$ and $IH(x,y)$. Then the coefficient matrices are both low pass filtered and high pass filtered in vertical direction and down sampled by factor of two, to create sub bands $ILL(x,y)$, $IHL(x,y)$, $ILH(x,y)$ and $IHH(x,y)$. The $ILL(x,y)$ represents approximation of input image $I(x,y)$. Then $IHL(x,y)$, $ILH(x,y)$ and $IHH(x,y)$ represent the horizontal, vertical and diagonal information of the input image $I(x,y)$ respectively. The inverse 2-D wavelet transform is used to reconstruct the original input image $I(x,y)$ from the sub bands $ILL(x,y)$, $IHL(x,y)$, $ILH(x,y)$ and $IHH(x,y)$. This involves column up-sampling and filtering using low pass and high pass filters for each sub images. Row up sampling and filtering with low pass and high pass filters and summation of all matrices would construct the original image $I(x,y)$ [1].

The wavelet coefficient matrices for EO and IR images are computed by applying DWT. This matrix contains approximation (LL), horizontal (LH), vertical (HL) and diagonal (HH) components of each image. The fused wavelet coefficient matrix is obtained by applying fusion rules (Average rule for LL components and maximum rule for the remaining). Finally, the Inverse Discrete Wavelet Transform (IDWT) is applied on the fused wavelet coefficient matrix to get fused image. The information flow diagram of DWT fusion is shown in Figure5.

3. Fusion Quality Metrics

Performance of fusion techniques can be evaluated using two types of analyses: Subjective Analysis and Objective Analysis. Subjective Analysis is based on personal opinion, interpretation and judgement. Objective Analysis is based on theory and numerical calculations. Objective Analysis on fused image is done using Fusion Quality Metrics. These are of two types, Reference metrics and No Reference metrics. Reference metrics involves comparison of fused image with a reference image whereas No Reference metrics do not require a reference image. No Reference metrics are computed in this application as it involves fusion of two different images and no single image can be taken as a reference. These metrics are used to compare the efficiency of each fusion technique and to find out the best performing technique. A set of 11 performance metrics are implemented in this fusion application, whose description is followed in the following section.

3.1 Standard Deviation

Standard deviation is a measure that is used to quantify the amount of variation of a set of data values. Low standard deviation indicates that the data values tend to be close to the mean of the set and high standard deviation value indicates that the data points spread out over a wide range of values. In image processing, standard deviation is variation of pixel values with respect to the mean of all pixel values of an image [7].

$$\sigma = \sqrt{\frac{1}{MN}\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}\left(I_f(x,y)-\mu\right)^2} \tag{8}$$

Where, M and N represents the number of rows and columns, μ is the mean of all pixel values in the fused image (I_f).

3.2 Entropy

Entropy is a measure of information content of an image. It is sensitive to noise and unwanted rapid fluctuations. It is high for the image with high information content [7].

$$He = \sum_{i=0}^{L} h_{I_f}(i)\log_2 h_{I_f}(i) \qquad (9)$$

Where (h_{I_f}) is the normalized histogram of the fused image (I_f). The unit of entropy is bits/pixel.

3.3 Cross Entropy

Cross entropy is used to verify the similarity in information content between input and fused image. Low values of cross entropy indicate that the input and fused images are almost similar [7].

Overall cross entropy of the input images I_1, I_2 and the fused image I_f is

$$CE(I_1, I_2 : I_f) = \frac{CE(I_1; I_f) + CE(I_2; I_f)}{2} \qquad (10)$$

Where

$$CE(I_1; I_f) = \sum_{i=0}^{L} h_{i_1}(i)\log\left(\frac{h_{i_1}(i)}{h_{i_f}(i)}\right) \qquad (11)$$

$$CE(I_2; I_f) = \sum_{i=0}^{L} h_{i_2}(i)\log\left(\frac{h_{i_2}(i)}{h_{i_f}(i)}\right) \qquad (12)$$

3.4 Spatial Frequency

Spatial frequency refers to the level of detail present in a stimulus per degree of visual angle. A scene with small details and sharp edges contains more high spatial frequency information than one composed of large coarse stimuli. This metric indicates the overall activity level in the fused image [7].

Spatial frequency criterion SF is:

$$SF = \sqrt{RF^2 + CF^2} \qquad (13)$$

Where row frequency of the image

$$RF = \sqrt{\frac{1}{MN}\sum_{x=1}^{M}\sum_{y=2}^{N}[I_f(x,y) - I_f(x,y-1)]^2} \qquad (14)$$

And column frequency of the image

$$CF = \sqrt{\frac{1}{MN}\sum_{x=1}^{M}\sum_{y=2}^{N}[I_f(x,y) - I_f(x-1,y)]^2} \qquad (15)$$

3.5 Fusion Mutual Information

Fusion Mutual Information indicates the degree of dependence of the fused image on the source images. The larger value of fusion mutual information implies better quality [7].

The joint histogram of source image $I_1(x,y)$ and $I_f(x,y)$ is defined as $h_{I_1 I_f}(i,j)$ and for source image $I_2(x,y)$ and $I_f(x,y)$ is defined as $h_{I_2 I_f}(i,j)$. The mutual information is defined as follows,

$$FMI = MI_{I_1 I_f} + MI_{I_2 I_f} \qquad (16)$$

Where

$$MI_{I_1 I_f} = \sum_{i=1}^{M}\sum_{j=1}^{N} h_{I_1 I_f}(i,j)\log_2\left(\frac{h_{I_1 I_f}(i,j)}{h_{I_1}(i,j)h_{I_f}(i,j)}\right) \qquad (17)$$

$$MI_{I_2 I_f} = \sum_{i=1}^{M}\sum_{j=1}^{N} h_{I_2 I_f}(i,j)\log_2\left(\frac{h_{I_2 I_f}(i,j)}{h_{I_2}(i,j)h_{I_f}(i,j)}\right) \qquad (18)$$

3.6 Fusion Quality Index

The range of this metric is 0 to 1. '1' indicates the fused image contains all the information from the source images.

$$FQI = \sum_{w\in W} c(w)(\lambda(w)QI(I_1, I_f|w) + (1-\lambda(w))QI(I_2, I_f|w)) \qquad (19)$$

Where $\lambda(w) = \frac{\sigma_{I_1}^{2}}{\sigma_{I_1}^{2} + \sigma_{I_2}^{2}}$ computed over a window and $c(w) = \max(\sigma_{I_1}^{2}, \sigma_{I_2}^{2})$ over a window and $c(w)$ is normalized version of $c(w)$ & $QI(I_1, I_f \mid w)$ is the quality index over a window for given source image and fused image [7].

3.7 Average Contrast

Contrast is a visual characteristic that makes an object or its representation in an image distinguishable from other objects and the background. In visual perception, contrast is determined by the difference in the colour and brightness of the object and other objects within the same field of view and higher contrast value is preferable [7].

$$C_{avg} = \frac{1}{(M-1)(N-1)}\sum_{x=1}^{M-1}\sum_{y=1}^{N-1}\left|\vec{C}(x,y)\right| \qquad (20)$$

Where, M and N represents the number of rows and columns of an image.

For an IR image, the contrast is the gradient calculated for the image as a single component:

$$\left|\vec{C}(x,y)\right| = \sqrt{\nabla^2 I(x,y)} \qquad (21)$$

$$\nabla I(x,y) = \frac{\partial I(x,y)}{\partial x}\hat{i} + \frac{\partial I(x,y)}{\partial y}\hat{j}$$

Where, ∇ = gradient operator

$I(x,y)$=Image pixel value at (x,y)

Average gradient reflects the clarity of an image. It measures the spatial resolution in an image i.e. larger average gradient indicates a higher resolution. Higher value of Average Contrast is an indication of better image quality.

For a colour image, the colour contrast is given by the average of gradients of Red, Green and Blue considered individually as follows:

$$\left|\vec{C}(x,y)\right| = \sqrt{\frac{\nabla^2 R(x,y) + \nabla^2 G(x,y) + \nabla^2 B(x,y)}{3}} \quad (22)$$

3.8 Average Luminance

Luminance describes the amount of light that passes through, or is emitted from a particular area, and falls within a given solid angle. It indicates the amount of luminous power perceived by an eye looking at the surface from a particular angle of view. Luminance is thus an indicator of how bright the surface will appear [7].

$$L_{avg} = \frac{1}{MN}\sum_{x=1}^{M}\sum_{y=1}^{N} I_f(x,y) \quad (23)$$

For colour image,

$$L_{avg} = \frac{1}{MN}\sum_{x=1}^{M}\sum_{y=1}^{N} \frac{R(x,y)+G(x,y)+B(x,y)}{3} \quad (24)$$

Higher luminance value represents the higher brightness value of an image.

3.9Energy

Energy returns the sum of squared elements in the Gray Level Co-occurrence Matrix (GLCM). It is also known as uniformity, uniformity of energy or angular second moment. The energy of an image lies between zero and one [7].

$$E = \sum_{i=1}^{8}\sum_{j=1}^{8} g(i,j)^2 \quad (25)$$

3.10Homogeneity

Homogeneity is a condition in which all the constituents are of the same nature. Homogeneity returns a value that measures the closeness of the distribution of elements in the Gray Level Co-occurrence Matrix (GLCM) to the GLCM diagonal i.e. if all the pixels in a block are within a specific dynamic range. The range homogeneity is from zero to one. Homogeneity is '1' for a diagonal GLCM [7].

$$I_{\hom} = \sum_{i=1}^{8}\sum_{j=1}^{8} \frac{g(i,j)}{1+|i-j|} \quad (26)$$

3.11 SNR

Signal to Noise Ratio will be high when the reference and fused images are alike. Higher value of SNR implies better fusion.

$$SNR = \frac{\mu}{\sigma} \quad (27)$$

Where, μ is the mean and σ is the standard deviation of the fused image.

4. System Requirements

Implementation of fusion in C#ImFuse, image fusion application, need some pre-requisites that include hardware equipment (only for real-time image fusion) and software setup. The details of both are discussed in the sections followed.

4.1 Hardware Setup

Hardware equipment includes EVS, Frame Grabber, RS-170 connectors and a computer. EVS has two imaging sensors (EO and IR) which operate using +12Vbattery. The outputs of the cameras are connected to the frame grabber through two RS-170 cables. The hardware setup used for implementing real-time image fusion is shown in Figure6.

4.1.1 EO and IR Imaging Sensor Specifications

The EO imaging sensor is a CMOS sensor that senses the reflected energy with the frequency of the energy reflected giving an image. It requires a light source to provide the image and is more sensitive than the eye. The IR imaging sensor senses based on the radiant energy emitted by objects. This cannot be detected by human eye as the wavelength of emitted radiations falls in infrared region of electro-magnetic spectrum. IR imaging sensor incorporates an uncooled 324x256 pixels micro bolometer. It has an internal heater to defrost its protective window. The technical specifications of EO and IR cameras are given in the Table 1.

4.1.2Sensoray Frame Grabber

A four-channel Sensory Frame Grabber (2255) is used for capturing image frames from both the cameras at a desired frame rate. Total capture rate is 60 frames/sec from each channels for NTSC colour video, but when 2 channels are used simultaneously, capture rate is 30 frames/sec each, or 4 channels at 15 frames/sec each. Here, two channels are used and so the maximum frame rate achieved is 30 frames/sec. The digitized output from the frame grabber is given to the computer by using USB cable [8].

4.2 Software Setup

A computer installed with Visual Studio (v2013 or higher) is required to develop this application. Fusion methods are implemented using EmguCV, a C#

wrapper for Open Source Computer Vision (OpenCV) image processing library in Visual Studio platform. EmguCV opens OpenCV library of programming functions, mainly aimed at real-time computer vision to C# developers. C#ImFuse was developed using Windows Forms(in C# programming language) [9].

4.2.1 Installing EmguCV

Working with images in Visual Studio C# requires external packages to be installed in the project. Respective .dll files of the package can be downloaded and included in the project. Using Package Manager Console (PMC) to install external packages is an easier way. Locate PMC in Visual Studio at Tools >Library Package Manger > Package Manager Console. Open it and type "Install-Package EmguCV"to install the corresponding package in the current project [10]. Using PMC, addition of packages into the project can be automated instead of manually going to the NuGet UI to add packages. The packages will automatically be downloaded from the internet, using the web-link specified in Tools > Library Packet Manager > Package Manager Settings > Package Manager > Packager Sources. EmguCV package for this application is downloaded from Ref. [11].

5.Real-Time Image Fusion

Real-Time fusion of images involves capturing the images in real-time, image registration and applying fusion techniques that results in a fused image. The Fusion process involves the steps shown in Figure 7.

5.1 Image Registration

Image registration is a process of aligning two or more images of the same scene. One image is taken as reference image (fixed image) and geometric transformations will be applied on the other image (moving image) to align with the reference image. Here, EO image is the reference image as it has higher FOV and transformations are applied to IR image. Image registration is done off-line for EO and IR images using Control Point image registration toolbox of MATLAB [12]. In Control Point image registration, the user has to select same feature points on both images manually as shown in Figure 8.Control Points (fixed points and moving points) are obtained from MATLAB and used to get the Transformation matrix (Affine Transform) using "CvInvoke.GetAffine()" command [6]. Affine Transformation is a 2x3 matrix, used to express linear transformations (rotations and scale operations) and translation (vector addition). When shapes in the moving image exhibit shearing, this transformation is applied. Straight lines remain straight and parallel lines remain parallel, but rectangles become parallelograms. A minimum of three non-collinear points are needed to infer affine transform. Affine transform obtained for images in Figure 8 is shown below:

$$\begin{bmatrix} -0.9673 & -0.033 & 66.3852 \\ 0.0035 & 1.0778 & -28.8946 \end{bmatrix}$$

The command "CvInvoke.WarpAffine()" transforms the image [6]. This results in a registered image (registered IR image in this case) as shown in Figure 9.

6. Results and Discussions

This application is capable of fusing two user-given images using four different fusion algorithms viz., Alpha blending, Laplacian Pyramid, PCA and DWT.

6.1Still Images

Once the application is run, the front end of the C#ImFuse appears as shown in Figure 10. The user has to select the images to be fused. These images must be of the size and size must be in powers of 2. If the images are of different sizes, the application pops up a window showing a message that the images are of different sizes. Later, the user has to select the fusion method from the drop down menu. C#ImFuse applies the selected fusion technique and gives fused image output along with the fusion quality metrics displayed in the 'Fusion Quality Metrics' pane. It also displays the time taken by the application in performing the fusion.

The images taken for fusion are in same FOV. Therefore, image registration is not required. Figure 11shows the EO and IR images obtained from Ref. [13].In Figure11(a), the lower part of the scissors is hidden behind the black wrapper. On the other hand, the IR image shows full image of the scissors because of the penetrating nature of IR camera. Therefore, in Figure 11(b), the hidden part of scissors and some holes on the wrapper, which can't be found in EO image, are visible, but colour information is not there. So, the fused image obtained by applying various fusion methods is expected to contain all the features of both the images.

6.1.1Alpha Blending

In Alpha Blending, fused images obtained by varying the transparency (using various α values) are shown in Figure12. In Figure 12(a), α is 0.2, so it gives more weightage to IR image, showing all the features of IR image like the holes in the wrapper, lower part of the scissors that is hidden in EO image etc. It retains the colour information of EO image. Similarly, in Figure 12(c), α is 0.8, so fused image elevates the features of EO image giving it high weightage while retaining features of IR image. In Figure 12(b), α is 0.5, the fused image shows that equal weightage is given to both the input images and this is nothing but a simple pixel by pixel averaging of input images. Alpha Blending results in a very smooth fusion, which is because of its high Fusion Quality Index compared to the other fusion methods, as shown in Table 2. It is a very simple fusion method and so the elapsed time for fusion is very less.

Table 3 shows variations in Fusion Quality Metrics as α is increased in its range [0, 1]. It is observed that the fusion performance in terms of these metrics is better for lower values of α where IR image is given high weightage.

6.1.2 Principle Component Analysis

PCA fusion results in an image, which shows dark background, similar to the fused images obtained with high alpha values in alpha blending. This means that dynamically calculated weightages highlight EO image than IR for this set of images. The fused image retains the features of both the input images. The overall performance of fusion is better than alpha blending and DWT, as per the Fusion Quality Metrics shown in Table 4. As this method involves calculation of weightages, it takes relatively more time to fuse the images.

The fusion of EO and IR images using PCA technique is shown in Figure13.

6.1.3 Laplacian Pyramid

Laplacian pyramid technique is observed to be edge-sensitive and highlights the edges of all the objects in input images. The fused image contains the edge information of the EO image and temperature highlighted edge information from IR image. This technique exhibits high Average Luminance (brightness), compared to other fusion techniques. Therefore, the fused images are relatively brighter. Variations in Fusion Quality Metrics with the number of decomposition levels of Laplacian Pyramid, is shown in Table 4. The number of levels of image pyramid is limited to n-1. This technique exhibits better fusion at lower levels of decomposition. The brightness of the fused image increases with increased levels of decomposition, which can be observed in Figure 14.

From the metrics shown in Table 2, it is inferred that Laplacian pyramid technique performs better than other fusion techniques. It has better fusion quality and the time elapsed for fusion is also relatively less.

6.1.4 Discrete Wavelet Transform

The fused image obtained by applying wavelet transform for one level of decomposition is shown in Figure15. The fused image contains temperature-sensitive information from IR image and colour-sensitive information from EO image. DWT exhibits high contrast in the fused image. It is a very time consuming technique as it involves pixel level operations. The fused images obtained by applying DWT and Alpha Blending exhibit similar properties, as per the Fusion Quality Metrics shown in Table 2.

A variation in Fusion Quality Metrics with decomposition levels is shown in Table 5. DWT shows relatively good fusion at higher levels of decomposition.

6.2 Real-Time Images

C#ImFuse captures real-time images from EO and IR cameras and applies the selected fusion technique. Figure 16(a) shows the EO image and 16(b) shows IR image captured in real-time.

6.2.1 Alpha Blending

Alpha Blending is applied on EO and IR images for α values 0.2, 0.5 and 0.8. The results are shown in Figure 17. As α is increased, the contents of EO image are highlighted. Fused image has high Homogeneity compared to other methods and so it appears close to the input images. The Fusion Quality Metrics for Alpha Blending in comparison with other methods is shown in Table 6.For small values of α, IR image is highlighted. It is a simple fusion method and consumes very less time than other fusion methods.

6.2.2 Principle Component Analysis

PCA fused image exhibits very good Fusion Quality Index compared to other techniques as per the Fusion Quality Metrics shown in Table 6. Therefore, the fused image shown in Figure 18 shows a very smooth fusion. Fused image highlights EO image as the Eigen value corresponding to the EO image is high in value. It is observed that PCA results in better fusion next to Laplacian Pyramid method.

6.2.3 Laplacian Pyramid

Laplacian Pyramid technique image exhibits very good fusion compared to other methods, as per the Fusion

Metrics in Table 6. The fused image appears very bright because of high Luminance. Fusion is performed up to four levels of decomposition and fused images are shown in Figure 19.It is observed that fused images gives high weightage to the edges of all the objects from images to be fused.

6.2.4 Discrete Wavelet Transform

DWT fused image exhibits high contrast compared to other methods. Its performance is observed to be very close to alpha blending, except that it is highly time consuming, involving complex operations. Figure 20 shows the DWT fused image for one level of decomposition of real-time EO and IR images. The time elapsed increases with increased levels of decomposition.

CONCLUSION

Four image fusion techniques viz., alpha blending, Laplacian Pyramid, PCA and DWT are implemented and tested on still images as well as real-time EO and IR images. The performance of these methods is evaluated using a set of 11 Fusion QualityMetrics. Based on fused images and Fusion Quality Metrics, it is concluded that the Laplacian pyramid based fusion method provides better results compared to the other fusion methods. Source code is provided to understand the fusion techniques and for easy implementation.

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Table 1 Technical Specifications of EO and IR imaging sensors

Technical Specifications	EO imaging sensor	IR imaging sensor
Detector Type	Focal Plane Array (FPA) uncooled micro bolometer	CMOS ¼’’
Field of View	36° (H) x 27° (V) with 19 mm lens	38° (H) x 25° (V) with 6.8 mm lens
Output Formats	Analog, CCIR/PAL composite video, 75Ω	NTSC/PAL Analog, Raw RGB, 1.0Vpp /75ΩComposite Video Signal
Input Power Supply	6 - 16 V DC	Digital Core 5V DC ~ 24VDC

Table 2 Fusion Quality Metrics (FQM) for still images (Figure 11)

Fusion Quality Metric	Alpha Blending (α = 0.5)	Principle Component Analysis	Laplacian Pyramid (levels =1)	DWT (levels =1)
Standard Deviation	25.5757	32.2085	**34.7746**	27.2323
Entropy	6.3523	5.7262	**6.9860**	6.4293
Cross Entropy	2.0490	1.0646	**3.9329**	1.9721
Spatial Frequency	13.9924	**18.9400**	12.3545	19.8477
Fusion Mutual Information	1.7346	**2.6086**	1.5196	1.5403
Fusion Quality Index	**0.5588**	0.2957	0.5516	0.5593
Average Contrast	2.3764	2.0254	2.5647	**3.3094**
Average Luminance	93.9382	57.8725	**185.7491**	93.8802
Energy	0.0014	**0.0064**	0.0006	0.0009
Homogeneity	0.3850	**0.5155**	0.3476	0.3198
SNR	3.6729	1.7968	**5.3415**	3.4473
Time Elapsed (ms)	**4**	11	6	254

Table 3Variation in Fusion Quality Metrics with α in Alpha Blending for still images (Figure 11)

Fusion Quality Metric	α value [0,1]								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Standard Deviation	**39.11**	34.82	30.99	27.82	25.57	24.47	24.70	26.20	28.81
Entropy	**7.01**	6.87	6.71	6.53	6.35	6.17	6.06	5.98	5.83
Cross Entropy	1.21	1.31	1.52	1.73	2.04	**2.16**	2.09	1.89	1.51
Spatial Frequency	15.70	14.79	14.17	13.90	13.99	14.42	15.19	16.23	**17.5**
Fusion Mutual Information	**2.62**	2.40	2.15	1.91	1.73	1.55	1.54	1.67	1.92
Fusion Quality Index	**0.626**	0.624	0.61	0.59	0.55	0.51	0.46	0.41	0.35
Average Contrast	**2.77**	2.66	2.56	2.46	2.37	2.26	2.18	2.11	2.06
Average Luminance	**122.8**	115.5	108.3	101.1	93.93	86.71	79.50	72.28	65.05
Energy	0.0006	0.0007	0.0009	0.0011	0.0014	0.0019	0.0025	0.0033	**0.0047**
Homogeneity	0.30	0.31	0.33	0.35	0.38	0.40	0.43	0.46	**0.49**
SNR	3.13	3.31	3.49	3.63	**3.67**	3.54	3.21	2.73	2.25

Table 4 Variation in FQMs with no. of levels of decomposition in Laplacian Pyramid for still images

Fusion Quality Metric	Number of levels of decomposition (L)							
	1	2	3	4	5	6	7	8
Standard Deviation	**34.77**	32.11	27.91	23.34	19.86	16.85	15.94	15.56
Entropy	**6.98**	6.90	6.73	6.52	6.28	6.04	5.94	5.91
Cross Entropy	3.93	4.06	4.34	4.93	5.61	5.81	5.83	**5.83**
Spatial Frequency	**12.35**	10.78	9.69	8.92	8.38	7.85	7.65	7.52
Fusion Mutual Information	**1.51**	1.33	1.13	0.98	0.91	0.91	0.89	0.89
Fusion Quality Index	**0.55**	0.51	0.45	0.38	0.33	0.28	0.26	0.25
Average Contrast	**2.56**	2.45	2.39	2.33	2.28	2.24	2.22	2.20
Average Luminance	185.74	190.97	197.88	205.01	210.69	214.94	216.57	**217.88**
Energy	0.0006	0.0007	0.0008	0.001	0.0012	0.0015	0.0017	**0.0018**
Homogeneity	0.34	0.36	0.37	0.39	0.40	0.41	0.42	**0.42**
SNR	5.34	5.94	7.08	8.78	10.6	12.75	13.58	**13.99**

Table 5 Variation in Fusion Quality Metrics with levels of decomposition in DWT for still images

Fusion Quality Metric	Number of levels of decomposition (L)							
	1	2	3	4	5	6	7	8
Standard Deviation	27.23	30.35	34.98	40.47	44.48	46.15	46.70	**46.88**
Entropy	6.42	6.62	6.85	7.03	7.25	7.27	7.26	**7.29**
Cross Entropy	**1.97**	1.76	1.58	1.48	1.36	1.37	1.40	1.38
Spatial Frequency	19.8	23.19	24.39	24.48	24.59	24.47	24.34	**24.34**
Fusion Mutual Information	**1.54**	1.43	1.40	1.46	1.47	1.49	1.50	1.49
Fusion Quality Index	0.559	0.563	0.568	0.580	0.568	0.567	**0.571**	0.570
Average Contrast	3.309	3.591	3.663	3.624	3.623	3.591	3.567	**3.570**
Average Luminance	93.88	93.84	93.87	94.01	93.87	93.89	**94.02**	94.01
Energy	0.0009	0.0006	0.0005	0.0005	0.0005	0.0006	**0.0009**	0.0008
Homogeneity	**0.319**	0.260	0.253	0.259	0.261	0.264	**0.27**	0.26
SNR	**3.44**	3.09	2.68	2.32	2.11	2.03	2.01	2.00

Table 6 Fusion Quality Metrics for Real-Time images (Figure 15)

Fusion Quality Metric	Alpha Blending (α = 0.5)	Principle Component Analysis	Laplacian Pyramid (levels =1)	DWT (levels =1)
Standard Deviation	30.0609	42.8137	**48.23**	30.3358
Entropy	6.6326	7.2122	**7.276**	6.6528
Cross Entropy	2.1073	1.6118	**3.6898**	2.1364
Spatial Frequency	4.9968	**7.5115**	7.1040	7.2406
Fusion Mutual Information	2.7948	**3.3433**	2.3464	2.6489
Fusion Quality Index	0.7067	**0.8216**	0.7631	0.7071
Average Contrast	1.4295	1.4559	1.5577	**1.8565**
Average Luminance	90.3692	122.555	**179.23**	90.3989
Energy	**0.004**	0.0022	0.0027	0.0028
Homogeneity	**0.7051**	0.6755	0.639	0.6303
SNR	3.0062	2.8623	**3.7161**	2.9799
Time Elapsed (ms)	**8**	27	11	869

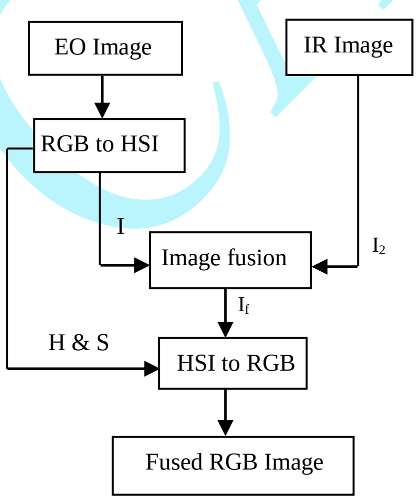


Figure 1Steps involved in image fusion of still images

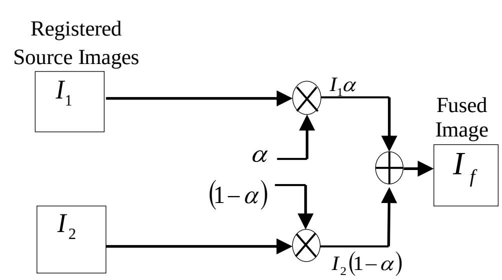


Figure 2 Alpha Blending based image fusion

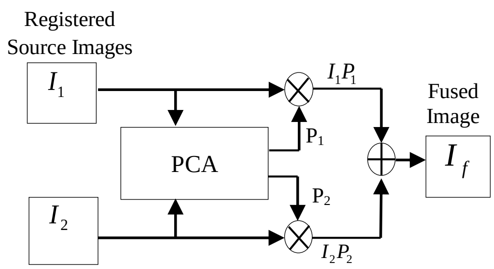


Figure 3PCA based image fusion

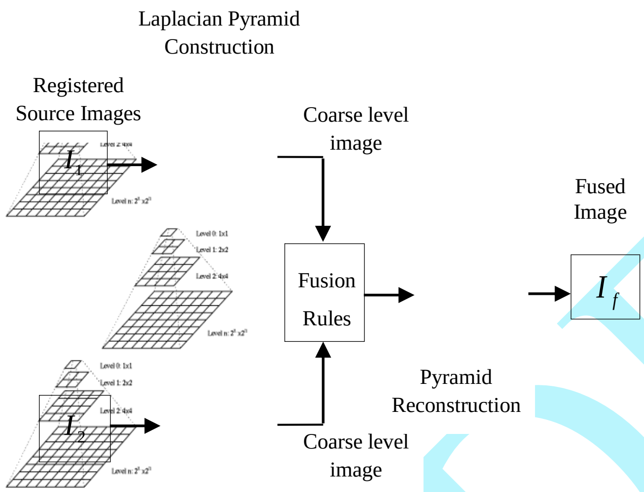


Figure 4 Laplacian Pyramid based image fusion

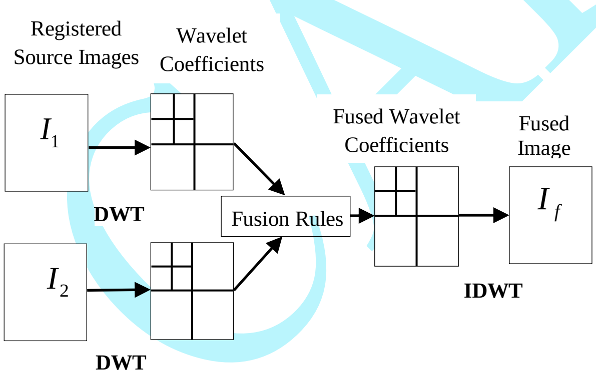


Figure 5 Wavelet based image fusion

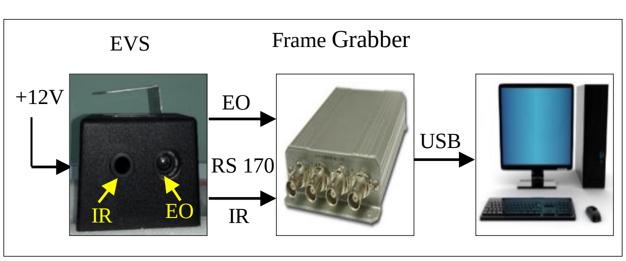


Figure 6Hardware Setup for Real-Time image fusion

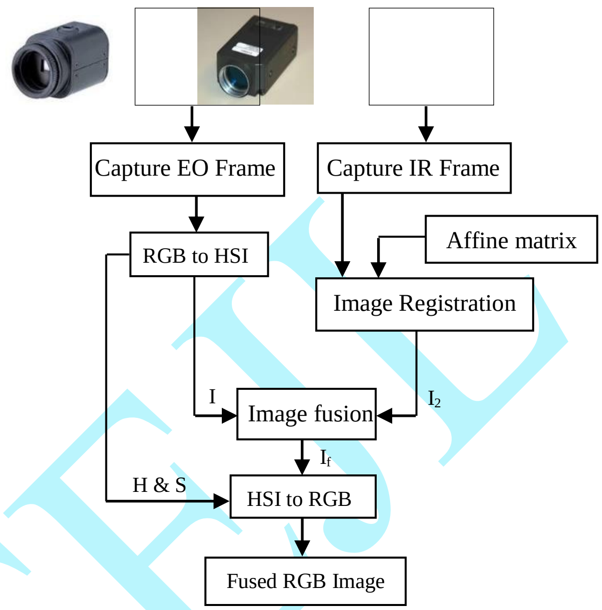


Figure 7Steps involved in real-time image fusion

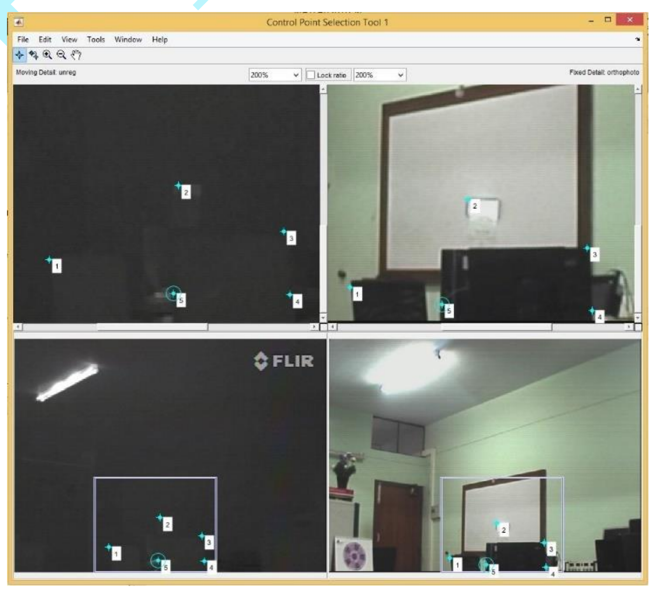


Figure 8 Point selection in Control Point toolbox for image registration in MATLAB

Figure 9 Registered IR image

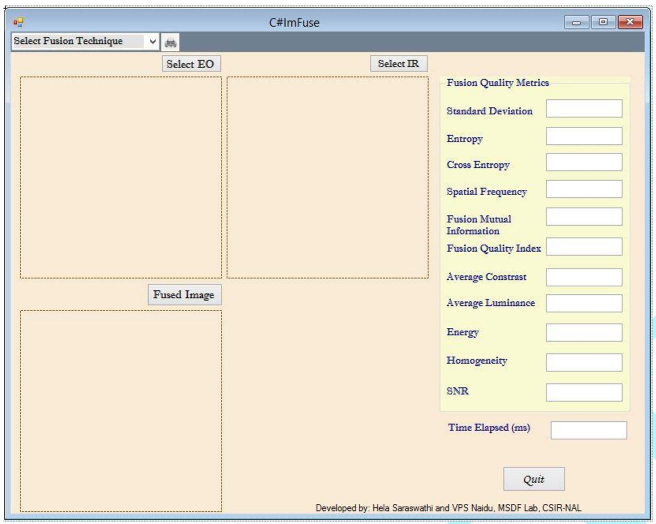


Figure 10Front-end view of C#ImFuse application

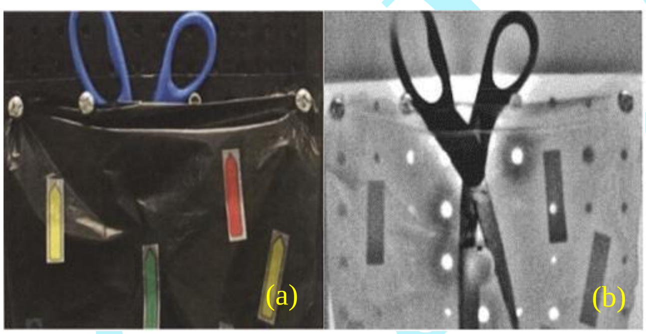
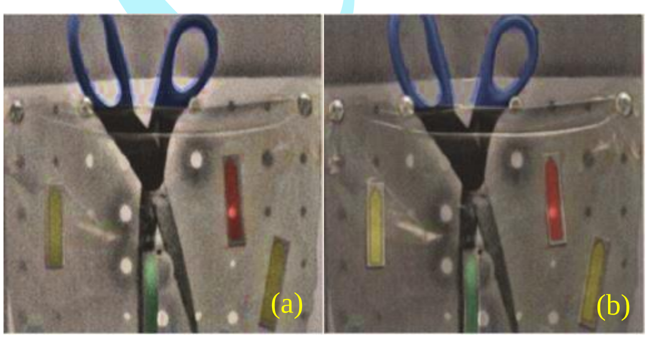


Figure 11(a) EO image, (b) IR image



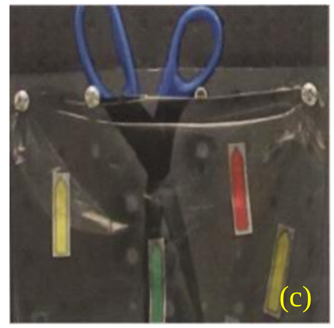


Figure 12Fused images for alpha (a) 0.2, (b) 0.5 and (c) 0.8

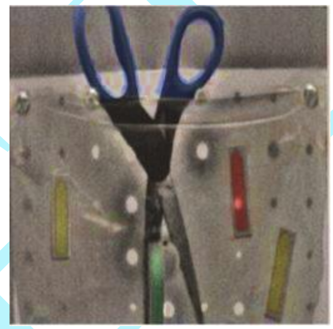


Figure 13PCA Fused image

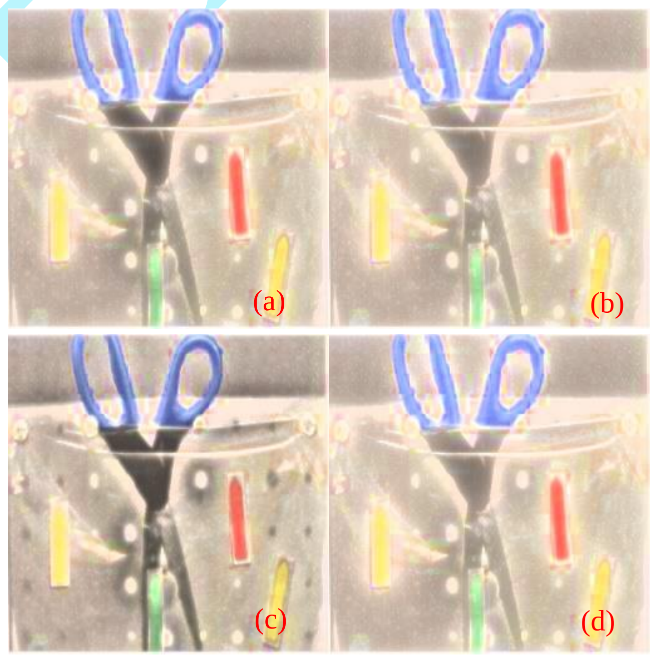


Figure 14Fused images with different Laplacian Pyramid levels(a) 1, (b) 2, (c) 3 and (d) 4

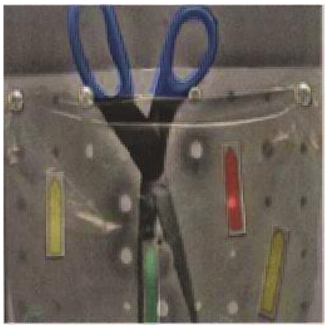


Figure 15DWT Fused image for one level of decomposition

Figure 16(a) EO image and (b) IR image

Figure 17Fused images for alpha (a) 0.2, (b) 0.5 and (c) 0.7

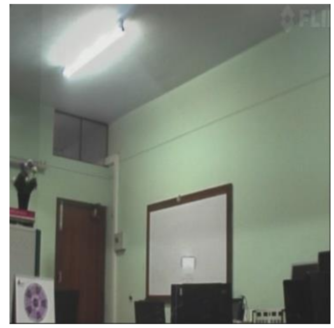


Figure 18PCA Fused image

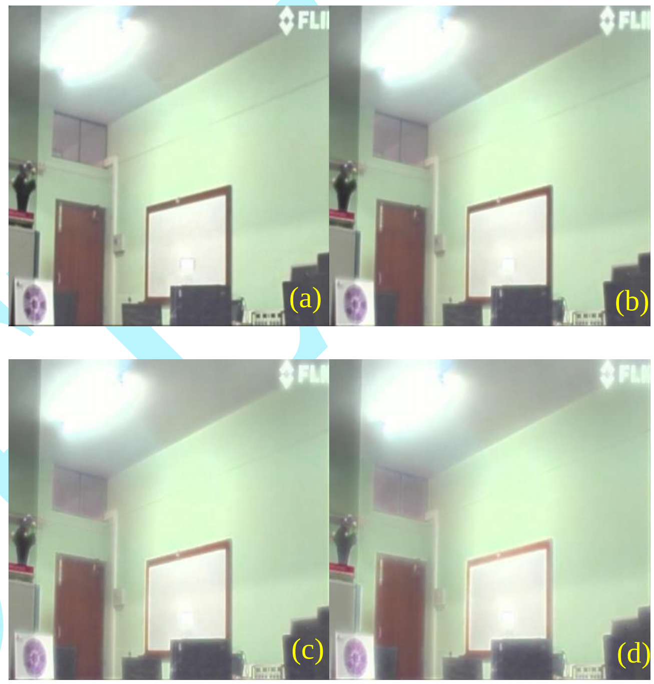


Figure 19Fused images with different Laplacian Pyramid levels (a) 1, (b) 2, (c) 3 and (d) 4

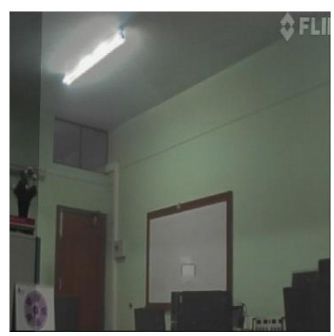


Figure 20DWT Fused image for one level of decomposition