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Image Fusion for Electrodynamics and Optical Dual Mode Tomography System

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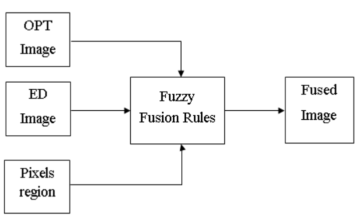
Graphical abstract



Abstract

In this paper, a novel fuzzy fusion method is proposed to combine the images obtained from dual modality (optical and electrodynamics) tomography sensors. The fuzzy rules designed are based on the features of each single mode sensor. Furthermore, the outcome of the proposed method is compared with the two mostly common image fusion methods; principal component analysis (PCA) and discrete wavelet transform (DWT). The fused image results of half flow and full flow solid/gas laboratory phantoms are presented in this paper. Matlab software was used to visualize and analyze the combined images. The results show that the proposed method has produces superior improvement in the quality of fused image for optical and electrodynamics dual mode tomography applications in the case of solid/gas flow.

Keywords: Image fusion; discrete wavelet transform; principal component analysis; dual mode tomography

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■1.0 INTRODUCTION

Dual Mode Tomography (DMT) is a method of combining different types of sensors to achieve a high quality cross sectional image of a pipe or conveyor. DMT consists of two components; hardware and software [1]. While the hardware component comprises the electronic circuits, data acquisition system and different types of sensors, the software component is made of signal processing, data analysis, image reconstruction and image fusion.

For the past decades, many attempts to design DMT systems for different types of flow regimes e.g. liquid-gas [2, 3] solid-gas [4, 5], liquid-liquid-gas [6] had been carried out. All of these DMT systems were designed based on the sensors response to material parameters. For example, electrical capacitance and electrical resistance DMT system were used for materials with very different capacity and conductivity parameters. Although hardware design is an important part of each DMT system, the procedure to reconstruct and fuse the image is equally important. The objective of image fusion method is to combine the information from multiple images from the same sense [7]. Image fusion method can be categorized into three levels; pixel level, feature level and decision level. The common fusion methods are successful in a pixel level due to their simple implementation and fast computation [8]. Principal component analysis and discrete wavelet transform are two common methods in pixel level of image fusion technique [9]. In addition to these general procedures, a fuzzy inference system (FIS) which works based on problem related rules should be used for imaging fusion.

In our previous work [10], we had developed an optical and electrodynamics DMT system for imaging solid/gas flow regime in a conveyor. The DMT system was designed based on the principle that electrodynamics sensors have high sensitivity around the wall of the pipe but unable to detect the particles towards the center of the pipe. While the optical sensors are able to detect objects near the center of the conveyor, they are inadequate when the concentration is more than 35% [11]. Therefore, the combination of these two systems can be used as a dual mode tomography to overcome the inherent shortcomings of these methods.

Our previous work was solely focused and limited to hardware design, whereas the current work zoomed in the imaging fusion methods which produce a fused image that has the information of both optical, and electrodynamics images.

A fuzzy based image fusion method has been developed and the quality of resulting images is compared against two common fusion methods; principal component analysis (PCA) and discrete wavelet transform (DWT).

2.0 IMAGE FUSION METHODS

Image fusion methods are categorized into two groups: spatial domain and transform domain [12]. There are a lot of pixel level fusion methods in each group, which are used to combine two images. Among these methods PCA in spatial domain and DWT in transform domain are the most common [13]. Thus, in this paper these two methods are discussed.

2.1 Principal Component Analysis (PCA)

PCA is a sub-space method in which the original inter correlated variables are dimensionally reduced for analysis to obtain uncorrelated variables [13]. In the case of image fusion, PCA method, detects the weight for each source image based on its component. This component is estimated by eigenvalues and eigenvectors of covariance matrix of images as illustrated in Figure 1.

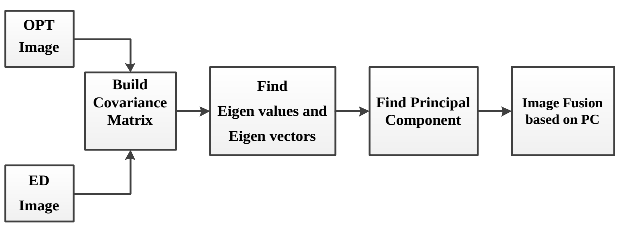

Figure 1 PCA fusion method procedure

The mathematics of PCA fusion method used to create image fusion is as follows [14]:

Let X and Y, n*n dimensional images with zero empirical mean as follows:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nn} \end{bmatrix} \text{ and } Y = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{n1} & \cdots & y_{nn} \end{bmatrix} \quad (1)$$

Reshape the images X and Y to a column vector and place them in a matrix as bellow:

$$XY = \begin{bmatrix} x_{11} & y_{11} \\ \vdots & \vdots \\ x_{nn} & y_{nn} \end{bmatrix} \quad (2)$$

Now calculate the covariance matrix of the XY and find the eigenvectors and eigenvalues of covariance matrix.

The eigenvectors related to the high eigenvalue are then used to find PCA weights for images as follow:

$$P_1 = \frac{V_1}{\sum V} \quad \text{and} \quad P_2 = \frac{V_2}{\sum V} \quad (3)$$

The fused image of PCA method is then calculated by the equation below:

$$Fused\ Image = P_1 X + P_2 Y \quad (4)$$

2.2 Descret Wavelet Transform (DWT)

Discrete Wavelet Transform (DWT) is a multi-resolution image decomposition tool, which provides a variety of channels representing the image feature from different frequency sub-bands at multi-scale [15]. In DWT, the approximation and detail component (The detail is divided into vertical, horizontal and diagonal) are separated when the decomposition is performed. The process of image fusion using DWT is shown in Figure 2.

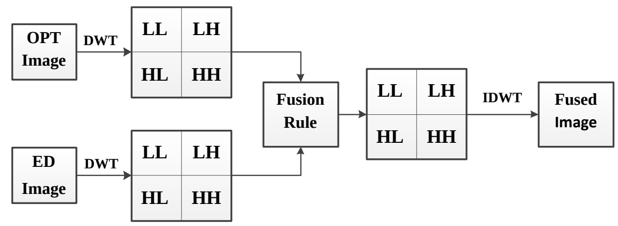

Figure 2 DWT procedure for image fusion method

DWT is separated into three steps:

Step 1. Implement DWT on both the input images to create wavelet lower decomposition. This is done by using a high pass and a low pass filter on each image and divide the result by 2 in each level of decomposition.

Step 2. Fuse each decomposition level by using different fusion rule. This fusion rule comprises the maximization, minimization, averaging, etc. of pixels intensity.

Step 3. Carry over Inverse Discrete Wavelet Transform on fused decomposed level, which is used to reconstruct the image, while the image. The outcome is the reconstructed image yielded the fused image (F).

2.3 Fuzzy Fusion

The above mentioned algorithms will only fuse all pixels with the same criteria [15], while in optical and electrodynamics DMT system the pixels region need to be included in making the decision. The reason is the sense area of each sensor is all unique, i.e. the electrodynamics will have more effects on a fused image for pixels close to the wall of the conveyor, while the optical sense has the most effect on the pixels near to the centre of the conveyor. Thus, a different type of decision rules based on the location of each pixel is required. A knowledge-based method is a fuzzy system that is able to change the decision based on the region of the pixels and the intensity of the images.

Fuzzy sets were introduced by Zadeh in 1965 [16]. A fuzzy set can be used as a fuzzy inference system (FIS), which maps multiple inputs to a single output. As illustrated in Figure 3, a fuzzy system consists of four main parts:

- Fuzzification converts the crisp input data to linguistic fuzzy sets called membership functions,
- Fuzzy rules govern the decision-making.
- Fuzzy inference engine whereby fuzzy operators apply to the fuzzify inputs based on pre-determined fuzzy rules and all the results are aggregated.
- Defuzzification whereby the final desired output is produced from a fuzzy set.

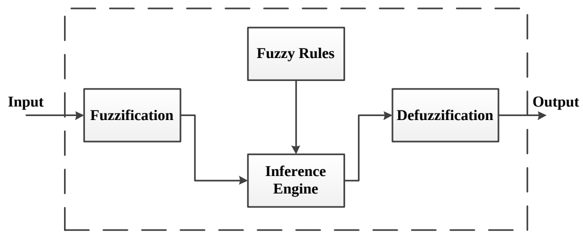

Figure 3 Block diagram of fuzzy inference system (FIS)

There are two common fuzzy inference engines; Mamdani in which the output is constant and Takagi-Sugeno in which the output is a polynomial [17]. There are many functions that can be used as a fuzzy membership functions e.g. Gaussian, trapezoidal or triangular functions to fuzzify the inputs. A fuzzy rule can be written as:

If x is A and y is B or z is C **Then** w is D

While A, B, C and D are linguistic fuzzy sets, x, y, z and w are variables.

Many fuzzy operators can apply the rules e.g. fuzzy And, OR operators which are used to define a rule. Besides that, minimization, maximization and averaging can be applied for aggregation procedure purpose.

3.0 METHODOLOGY

The whole procedure of optical and electrodynamics DMT system for solid/gas flow regime is shown in Figure 4.

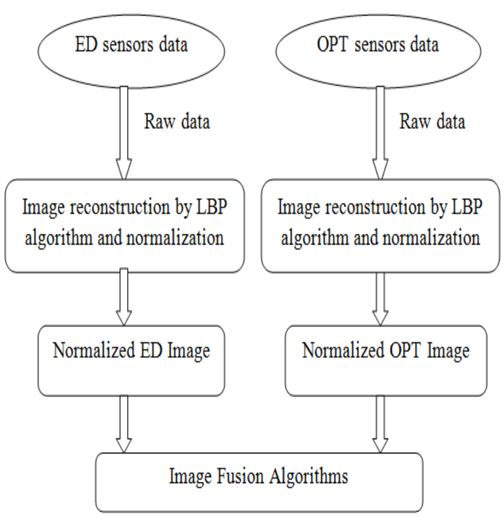

Figure 4 Image fusion process for optical and electrodynamics DMT system

We compared the image fusion methods obtained from PCA, DWT and fuzzy system in half flow and full flow solid/gas regime. The half and full flow were obtained from DMT laboratory built system. Then, the raw data was simulated using the Matlab software based on the LBP algorithm to reconstruct the image for each single mode. The 32*32-matrix size was used in each reconstruction image of electrodynamics and optical tomography. The procedure was then normalized for each image between [0, 1] interval. Finally, the normalized images were manipulated using fusion method to extract the fused image.

3.1 Hardware Design

Sixteen electrodynamics sensors were mounted inside a pipe wall and the optical sensors were fabricated using two projections. Each projection comprised 16 pair of transducers.

3.2 Image Fusion

After the LBP reconstructed images of each single mode was normalized between [0, 1] interval, the fusion method then was applied to these images.

For the PCA fusion method, the procedure mentioned in section 2.1 was applied. The parameter in PCA method remained unchanged. However, for the DWT fusion method, some parameters were adjusted to yield high quality images. These parameters include the **mother wavelet** e.g. Haar, Daubechies, Symlet, etc. The user can also define the number of decomposition levels and the fusion rules. In our experiment, a Haar **mother wavelet** in level one was selected for image fusion using DWT method. Then a maximization method was considered for approximation and detail fusion of two images.

The proposed fuzzy fusion process is shown in Figure 5, whereby the intensity of pixels and the region of pixels in each image provide the inputs to the fuzzy system. Then a fuzzy inference engine is used for decision-making based on the fuzzy rules. The result is aggregated and defuzzificated to produce the intensity of output pixel.

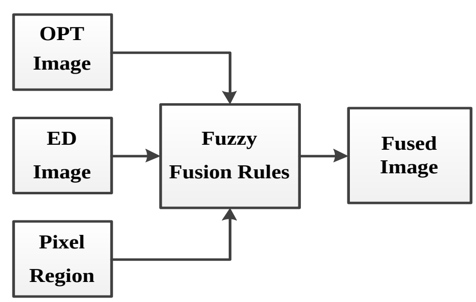

Figure 5 Proposed fuzzy fusion method

Gaussian membership functions are applied for all input and output whereas linguistic fuzzy sets are based on equation 5:

$$\mu(x) = e^{-\left({(x-a)^2}/{2\sigma^2}\right)} \quad (5)$$

Where
x is the distance from center
a is the position of the center of the peak of Gaussian function
σ is the standard deviation

As shown in Figure 6, an FIS system with five fuzzy sets in each input and output are taken into account.

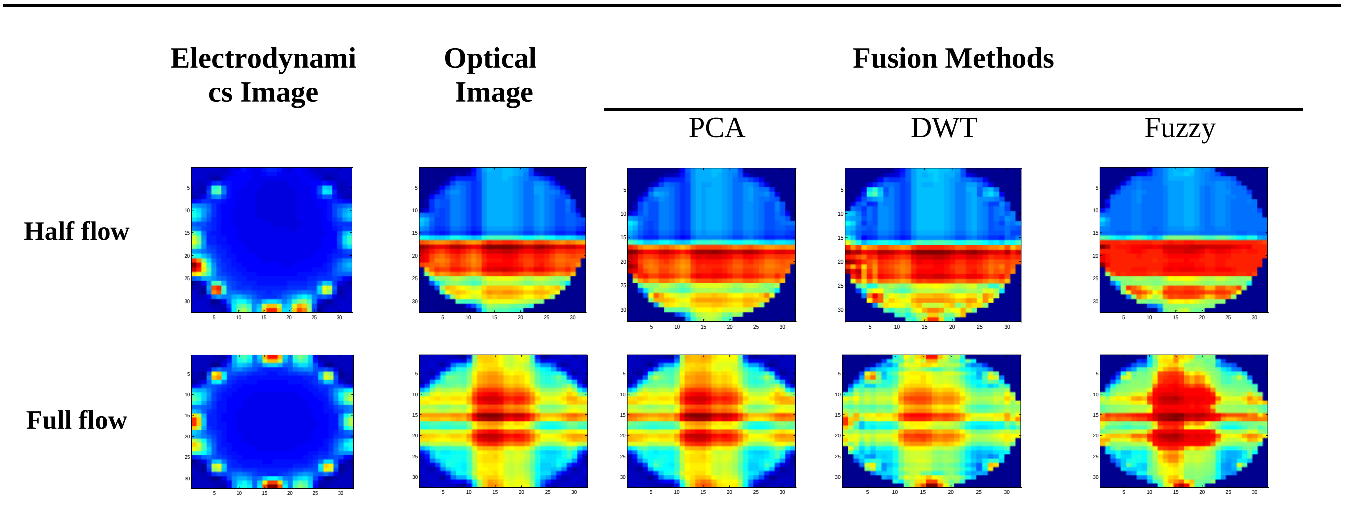

Figure 8 Image fusion produced by different methods

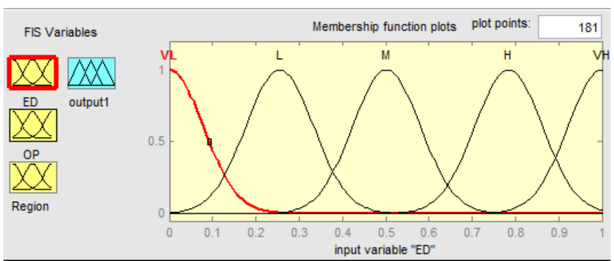

Figure 6 FIS with three input, one output and five membership functions for inputs 1 and 2

The intensity of each pixel in an image is converted to linguistic fuzzy sets and labeled as follows:

U={very low, low, medium, high, very high}

As for the third input, which is called the region and is the distance from the center of images, the following linguistic sets are used:

V={near center, center, far center}

The membership functions of the region input are presented in Figure 7. This input plays an important rule for fuzzy decision.

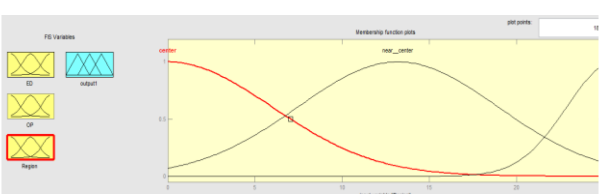

Figure 7 Membership functions of the region input

A Mamdani inference engine is referred to interpretation for rules porpuse. The fuzzy operator selected is as follows: Firstly, minimization for OR operator, secondly, maximization for AND operator and aggregation. Finally, a centroid method is used for defuzzification.

In total, 75 rules based on membership functions of each input (5 for electrodynamics, 5 for optical and 3 for region) exist in fuzzy rule database. Some of the typical Fuzzy rules to be considered in the application are as follows:

If Ed is Low and Op is Low and Region is Center then output is Low
If Ed is Low and Op is High and Region is Near-Center then output is Medium
If Ed is High and Op is Medium and Region is Far then output is High
If Ed is Medium and Op is High and Region is Center then output is High
If Ed is Medium and Op is very High and Region is Center then output is very High

As shown in Figure 6 and 7 there are five membership functions for electrodynamic and optical image inputs and three membership functions for region input. Therefore, our fuzzy system consists of 75 rules.

3.2 Quality Metrics

Two common quality metrics; mean square error (MSE) and peak signal to noise ratio (PSNR) have been utilized to compare the image fusion that was produced from the fuzzy system, DWT and PCA. The mathematical formulas of these metrics are given in equation 6 and 7:

$$\mathrm{MSE} = \frac{1}{m*n}\sum(X-Y)^2 \quad (6)$$

Where X is the original image, Y is the fused image and (m, n) are the number of pixels in the rows and columns of the images. The PSNR defined as:

$$\mathrm{PSNR} = 10\log(1/\mathrm{MSE}) \quad (7)$$

■4.0 RESULTS AND DISCUSSON

The data used in this paper are obtained from electrodynamics and optical DMT system. No such real image was captured to evaluate the quality of images obtained from the different fusion methods. Therefore, half flow and full flow regimes were simulated using the Matlab software. These phantom simulated images consist of two numbers; zero for existence of solid and one for air. Figure 8 presents all image generated from different fusion methods. Red color in all images represents high concentration of particles whereas yellow and green colours mean low concentration, and blue color is the empty area. Figure 8 also indicates that electrodynamics tomography is applicable for near wall charges, while optical tomography can detect the near center solids. In addition, the Figure 8 also shows both modes contain the information for the fused images.

The PSNR and MSE obtained from all methods for half flow and full flow depicted in Table 1 and Table 2 respectively. The tabulated results show that the developed fuzzy fusion method yields better performance and quality as compared to PCA and DWT methods. Due to efficiency of the proposed fuzzy method, the PSNR (27.654, 19.459) and MSE (0.063, 0.1429) are higher efficiency than other methods in the case of half flow and full flow solid/gas regimes. It can also be noted that the worth PSNR and MSE are belong to electrodynamics tomography where the sensors only sense the area near electrodes.

Table 1 PSNR and MSE for all methods for half flow regime

	ED	Op	PCA	Wavelet	Fuzzy
PSNR	13.197	26.2081	26.07	26.044	**27.654**
MSE	0.2672	0.0727	0.0738	0.074	**0.063**

Table 2 PSNR and MSE for all methods for full flow regime

	ED	Op	PCA	Wavelet	Fuzzy
PSNR	6.0173	18.0023	19.4067	19.0780	**19.459**
MSE	0.5479	0.1653	0.1436	0.1484	**0.1429**

The results in Table 1 and Table 2 also indicate that after fuzzy fusion, the PCA method performs better than wavelet transform; the reason is that wavelet method depends on the parameters, which are defined by users. Adjusting these parameters such as the selection of the **mother wavelet**, fusion rule etc. can change the result of the wavelet transform.

■5.0 CONCLUSION

In this paper a new pixel based fusion method for optical and electrodynamics DMT system is developed based on fuzzy inference system. Furthermore, a comparison between common fusion methods e.g. principal component analysis and discrete wavelet transform with proposed fuzzy based fusion method was investigated. Two experimental laboratory phantoms (half and full flow solid/gas) are used for method validation. The experimental results show that fuzzy rule based method has superior improvement on the fused image for the case of solid/gas flow.

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