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Image Fusion Using Fuzzy Logic Pixel Fusion for Dual Modality Tomography System

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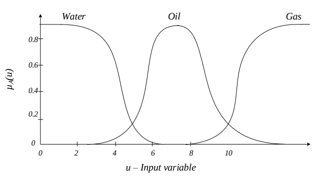
Graphical abstract



Abstract

Process tomography has been widely investigated and developed over time. The aim of this method is to measure the cross-sectional distribution of multiphase flow parameters based on its sensing technique. These single modality approaches has its own limitation whereby combination of two or more modality could overcome this issue. Therefore, a dual modality tomography (DMT) emergence of electrical capacitance sensors and ultrasonic sensor arrays for multiphase liquid mixture measurement was proposed. This paper presents an image fusion model using fuzzy logic pixel fusion method to integrate information for multisensory system such as DMT. A simulation analysis was carried out to perform image fusion on both ECT and UT input images. The developed fusion model proven to be successful in visualizing multiphase flow measurement. Thus, further validation and assessments were employed on the acquired results.

Keywords: ECT tomography; electrical capacitance; multimodality; dual modality; sensor; multiphase flow measurement

1.0 INTRODUCTION

Process tomography (PT) is regarded as a successful method for multiphase flow measurement in a variety of industrial field such as oil and gas industries, palm oil production, and food processing. PT in recent years has been developing well due its method in visualizing cross-sectional tomographic images across a pipeline conveyor where it is very useful for flow monitoring involved fields.

However, such system is single-modality type of tomography (SMT) whereby it often suffers from insufficient data to reconstruct quality tomographic images. Different SMT has particular sensing principle which usually suits for a particular type of measurement such as liquid-liquid mixture or liquid-gas mixture circumstances. Due to the limitation of the sensor, a multisensory system or dual-modality tomography (DMT) could further overcome such limitation thus further improve the results. The basic SMT and DMT system can be illustrated as below Figure 1.

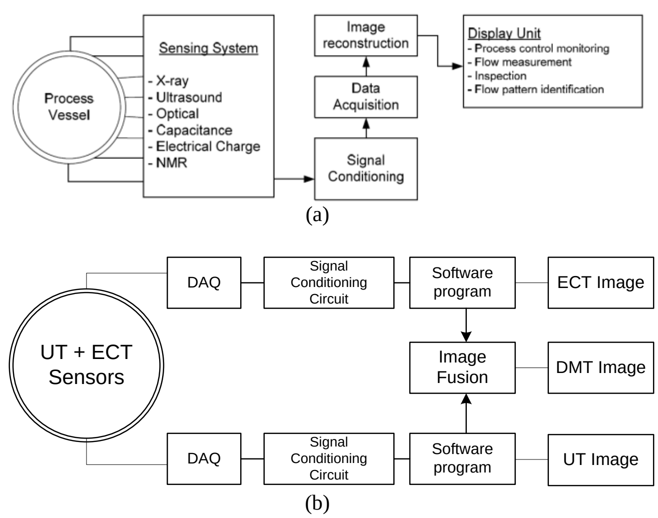


Figure 1 Tomography system block diagram; (a) single modality tomography (b) dual modality tomography

A successful DMT system must allow individual SMT sensor data to be collected and combined effectively [1]. Such system will encourage a systematic approach in contrast to the current PT systems that are usually complex, expensive and single-approach based.

This research has proposed the composition of electrical capacitance tomography (ECT) and ultrasonic tomography (UT) system to as a DMT system. The hardware design of DMT system was proposed and further discussed in [2].

2.0 IMAGE FUSION

The aim of a successful DMT system is to offer a comprehensive, integrated and synchronized processing platform. Many researchers have carried out studies on multimodality systems [3-6]. Mostly, the challenge of DMT is to combine information obtained from each SMT as fused image result which uses image fusion method. Image fusion has emerged as a new and promising research in this area. The basic hardware design and image reconstruction technique of ECT and UT system is discussed in [7, 8]

Image fusion is a process of combining information from two or more acquired images into a more informative single image namely fused image. It can be categorized as of the following [9]:

1. Low-level: Using transform domain algorithm to create fused image.
2. Mid-level: Using wavelet transform method
3. High-level: Fusion decision can be calculated using fuzzy logic approach.

2.1 Fuzzy Logic for Image Fusion

The high-level fusion using fuzzy logic approach is preferable for this research whereby the data information fusion process can take place at different levels of pixel value. The image results acquired from SMT are presented in tomographic pixel based image. These images are discrete into a 64 x 64 pixel as in Figure 2.

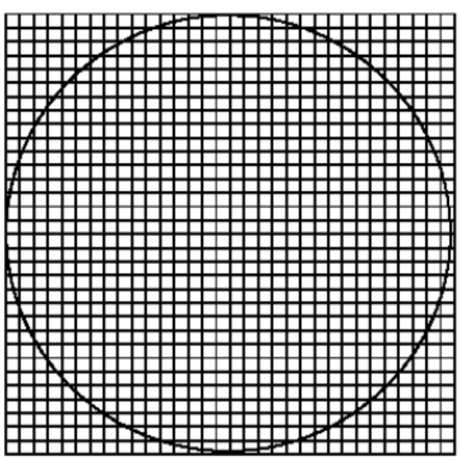


Figure 2 64x64 cross-section image pixel format

In pixel-level fusion, the image fusion process should combine useful relevant information from the input images to the composite image. The algorithm is responsible to decide its related information to be fused. Here, a fuzzy logic pixel fusion (FLPF) has been developed to combine images from ECT and UT.

Basically, fuzzy logic is an expansion from a superset of conventional Boolean logic to handle the concept of partial truth which best suits non-linear system such as DMT. The fuzzy logic approach was implemented through Mamdani Fuzzy Inference System (FIS) using Fuzzy Logic graphical user interface (GUI) tools provided in Matrix Laboratory (Matlab) software.

A conventional Boolean logic can be defined as follows:

$$\mu_x(u) = \begin{cases} 1 \ if\ u \in x \\ 0 \ if\ u \notin x \end{cases} \quad (1)$$

where $\mu_x(u)$ is the membership function of the set x. The main disadvantage of this method is the failure to evaluate information between values 0 and 1 which only partially belong to the fuzzy set.

Fuzzy logic allows partial membership for a closed variable interval of 0 to 1.

The measurement interest is to obtain three phase components in a single fused image namely; water, oil and gas. The fuzzy variable can assume different labels defined by linguistic values using the stated components as in Figure 3:

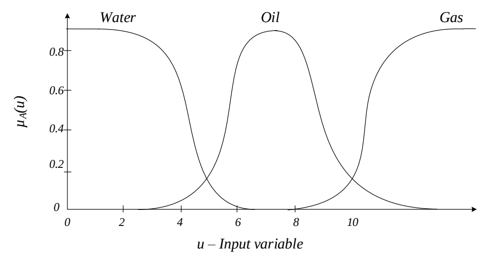


Figure 3 Fuzzy variable using linguistic values for water, oil and gas three phase components

The developed FLPF algorithm composite Z-shaped function and S-shaped function to perform a Z-S combination function which is similar to the sigmoid membership function [10]. The Z-shaped, S-shaped function and Z-S combination function is represented as in Equation (2), (3) and Equation (4) respectively [9]:

$$\mu_A(u) = \begin{cases} 1, \ u \le a \\ 1 - 2\frac{(u-a)^2}{(a-b)^2}, \ u > a, u \le \frac{a+b}{2} \\ 2\frac{(b-u)^2}{(a-b)^2}, \ u > \frac{a+b}{2}, u \le b \\ 0, \ u \ge b \end{cases} \quad (2)$$

$$\mu_A(u) = S(u; a, b, c) = \begin{cases} 0, \ u \le a \\ \frac{2(u-a)^2}{(c-b)^2}, \ a \le u \le b \\ 1 - \frac{2(u-c)^2}{(c-a)^2}, b \le u \le c \\ 1, \ u \ge c \end{cases} \quad (3)$$

$$\mu_A(u) = \frac{1}{1 = e^{-a(u-b)}} \quad (4)$$

where $\mu_A(u)$ is a fuzzy membership degree of u in the fuzzy set a. The conventional Boolean logic, Z-shaped, S-shaped and Z-S combination shaped fuzzy sets characteristic functions are illustrated as in Figure 4.

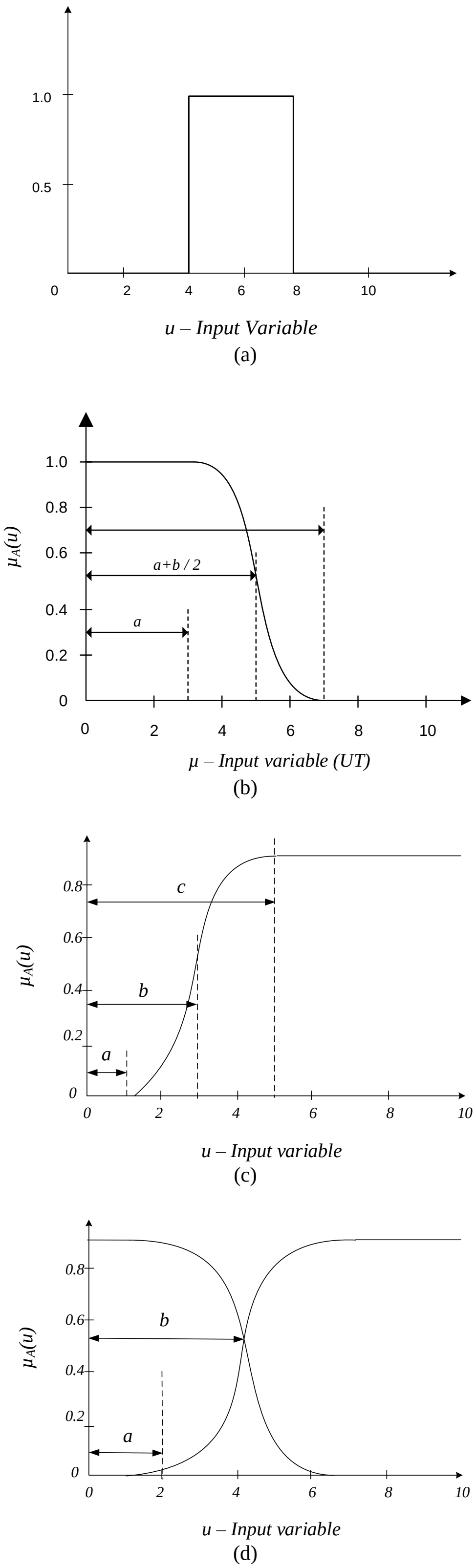


Figure 4 Fuzzy membership function of (a) conventional Boolean logic, (b) Z-shaped function, (c) S-shaped function and (d) Z-S combination function

The input image was normalized value 0 to 1 and its color intensity is represented as colorbar to differentiate between water, oil and gas materials. The developed FLPF is a two input (ECT and UT) with Mamdani FIS to perform image fusion.

■3.0 RESULT AND ANALYSIS

A static distribution flow model was simulated using phantom flow condition of water-oil-gas compositions. The composition condition is shown in Figure 5.

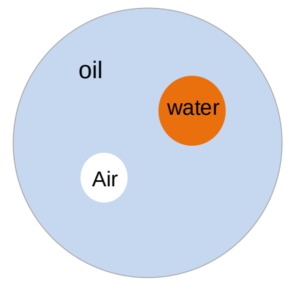


Figure 5 Water-oil-gas flow compositions reference

Both ECT and UT are responsible to reconstruct individual tomographic image using SMT approach before FLPF take place to produce fused image. The simulated test result of the input images and fused image are presented in below Figure 6.

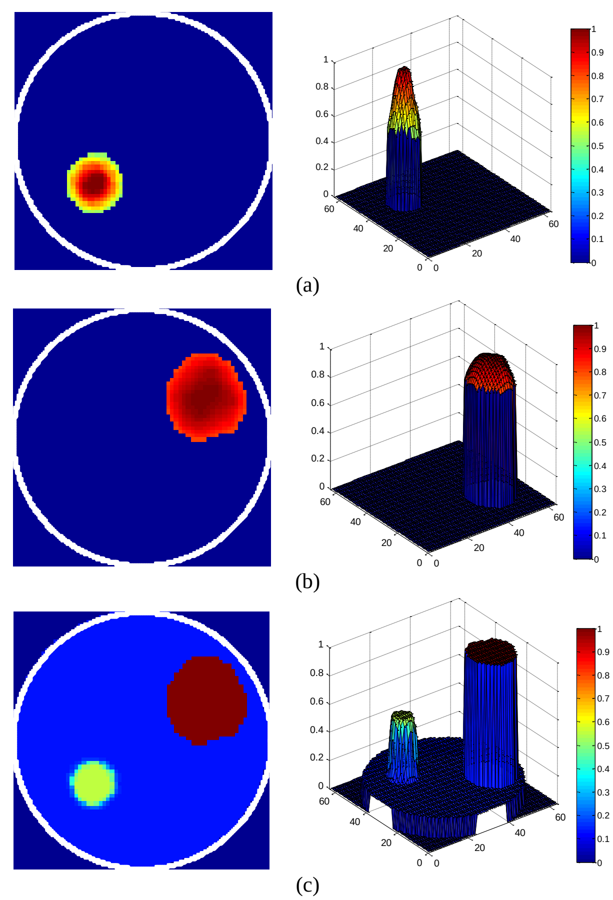


Figure 6 Image fusion using FLPF: (a) oil-gas image of ultrasonic tomography (b) oil-water image of electrical capacitance tomography and (c) fused image with oil-water-gas of dual modality tomography

3.1 Image Quality Assessment

To verify the performance of the reconstructed images and fused image, the linearity between the reconstructed image and reference image has to be measure. A correlation coefficient (*r*) method as in Equation 10 was applied to each image [11].

$$r = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{(\sum_m \sum_n (A_{mn} - \bar{A})^2)(\sum_m \sum_n (B_{mn} - \bar{B})^2)}} \qquad (4)$$

where A is the reference image, $\bar{A}$ is the mean of the reference image, B is the reconstructed image and $\bar{B}$ is the mean of the reconstructed image. The analysed result is presented in Table 1 below:

Table 1 Correlation coefficient for UT, ECT and DMT images

Process Tomography	UT	ECT	DMT
Correlation Coefficient *(r)*	0. 8527	0. 8978	0. 8388

The correlation assessment method is based on normalized correlation to match the pixel value across the images. This method is preferable because of its ease in the hardware implementation thus it is useful in real-time applications [9].

Evaluated results from Table 1 shows that the reconstructed images are highly correlated to the reference image. Which mean, the developed FLPF image fusion method has manage to combine sufficient information from the input images for DMT system.

■4.0 CONCLUSIONS

This paper presented an image fusion method using a developed FLPF algorithm to fuse input images from each SMT system. The acquired input images are successfully fused to present three phase components in tomographic format. The fused results content sufficient information from the input images which is highly correlated to these images.

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