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A REVIEW ON APPLICATIONS OF OPTICAL TOMOGRAPHY IN INDUSTRIAL PROCESS

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Abstract-This paper reviews some of the recent applications of optical tomography as a measurement tool for process parameters measurement such as flow concentration profiles, velocity profiles, and mass flow rate. The attentions that have been received by the optical tomography system for the applications of industrial parameters measurement are mainly because of the radiation safe emission of light sources to human or environment, fast response time, non-intrusive technique, and established models of light propagation through media or medium of interest thus making the solutions of forward and inverse problems to be relatively simpler to accomplish. The reports of the experimental result in this paper are mainly based on the previous works done by researchers in the area of optical tomography application where the main aspects are discussed. As a whole, the optical tomography can be applied to measure the velocity of beads in flow rig, measuring bubbles flow, flame imaging for combustion rate estimation, and flow concentration profile. Most of the applications as mentioned are

discussed in this paper. In the final parts of this paper, independent component analysis (ICA) is suggested to measure the turbidity of liquid with the air-bubble flow in a vertical pipe column.

Index terms*:* optical tomography, process tomography, flow imaging, concentration profiles, turbidity, attenuation coefficient, independent component analysis.

I. INTRODUCTION

Tomography is defined from a Greek word which “tomo” meaning “to slice” while “graph” meaning “image”. The definition word tomography from the *Oxford English Dictionary* is: “Radiography in which an image of a predetermined plane in the body or other object is obtained by rotating the detector and the source of radiation in such a way that points outside the plane give a blurred image. Also in extended use, any analogous technique using other forms of radiation”. From the Encyclopedia Britannica eb.com, they state tomography as: “Radiologic technique for obtaining clear X-ray images of deep internal structures by focusing on a specific plane within the body. Structures that are obscured by overlying organs and soft tissues that are insufficiently delineated on conventional X-rays can thus be adequately visualized”. Tomography can also be defined as a process of obtaining plane section image of an object [1]. Based on the definition mentioned before, tomography has been widely applied in the medical field where the technique was also used on to check for bone fractures and to detect diseases such as tumors or cancers. Moreover, tomography technique has been successfully applied in the area of process industrial as this technique can be operated without intruding or invading the object or particles conveyed in a material distribution line such as pipeline or pneumatic conveyor [2].

The term "industrial process tomography" refers to non-invasive visualization techniques which are still developing but have already contributed to the optimization of certain industrial processes [3]. For an example, tomography method was used in the oil and gas industries, to increase the efficiency and productivity of the process by detecting any irregularities of the process functions [2]. Thus, necessary actions can be taken to compensate the process and to avoid any disturbances in the process. Furthermore, the visualization of material properties at different spatial position in cross section is another major advantage of tomography technique which cannot be achieved using any conventional single point instruments [4]**.** It can be observed from most of the process tomography applications, the common objectives are to obtain mass flow rate profile and velocity of the flow [5]. Sensors for process tomography can be divided into two types: soft-field and hard-field sensors. The output of a soft-field is dependent on the distribution of material in the sensing volume [6] where capacitance, magnetic and electrical charge are examples of the soft-field sensors. On the other hand, hard-field sensor is sensitive to the medium's parameters regardless of the sensor's orientation, thus the data collection process requires linear interpretation and the sensitivity can be assumed to be homogenously distributed for every sensor's orientation [7]. Optical and gamma-ray were included in hard-field sensors where the image reconstruction algorithms are relatively simpler to implement as compared to soft-field sensor [8].

In general, a tomography system can be divided into three main parts which are sensors, data acquisition system, and image reconstruction algorithm [9] as shown in figure 1. There are several types of sensors that can be used in process tomography such as optical, electrodynamics, gamma ray, positron-emitting radionuclide (tracer), ultrasound, and rods pair (for electrical impedance). Each type of sensor has its advantages and disadvantages. The proper selection of sensor should be done by pre-classifying the properties of the medium to measure thus matching it with the best type of sensor, identifying the parameter to measure, total cost, and technical or practicality issue. Next section will discuss the fundamental of optical tomography.

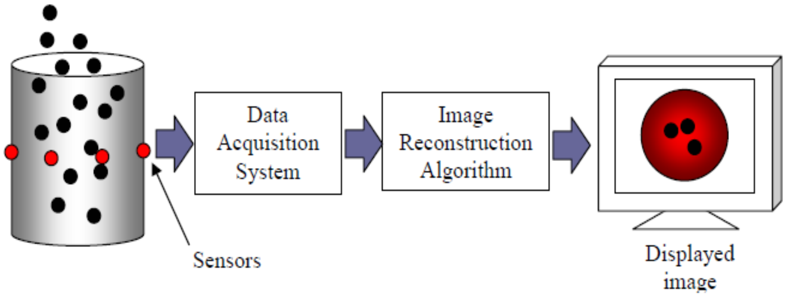


Figure 1. The main components of process tomography

II. FUNDAMENTAL OF OPTICAL TOMOGRAPHY

Optical tomography is one of the popular techniques that have been used in process tomography. Emitters and receivers pairs are required in this system where the light from the emitters will propagate into the medium conveyed in a vessel for instance where at the other end of the vessel boundary, the receivers will be supposed to detect the emitter's light [9]. The emitters can be Light Emitting Diode (LED), halogen bulb, laser, or infrared while the receivers or detectors can be photodiode, phototransistor, or photomultipliers [9]. Optical sensor has become the popular choice in the industry due to cheap prices of optical transducers, relatively straightforward and simple operation as compared to the other sensors such as capacitance sensors [10]. Moreover, optical sensors are capable of measuring the high-speed flowing particles since it can provide fast response time [11]. Therefore, optical tomography can provide a high frame rate which enabled through electronic switching of LED's and laser diodes and may be applied in high pressure level processes [12].

III. SYSTEM DESIGN

In optical tomography, the arrangement or alignment of the sensor plays the important role whether the design is successful or not. An optical sensor consists a set of emitter and receiver which should be arranged properly. It means that the light from the source/emitter which travels in the medium should be detected by the receiver [9]. Most of the pipes and vessel in manufacturing and industry have poor transparency (mostly opaque). Hence, a good design of optical windows are required to ensure the light mostly received by the receivers [13]. There are several projections that could be Ibrahim employed [14] as concluded in Table 1 and figure 2.

Table 1: Types of optical projections

Projection Type	Figure
Two orthogonal projections consisting of several parallel views	Figure 2 (a)
Two rectilinear projections consisting of several parallel views inclined at 45° to one another	Figure 2(b)
A combination of two orthogonal and two rectilinear projections	Figure 2(c)
Three fan-beam projections	Figure 2(d)
Four fan-beam projections	Figure 2(e)

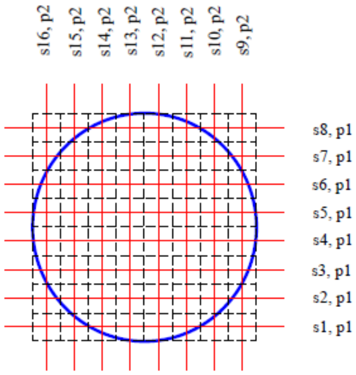


Figure 2(a). Orthogonals projections

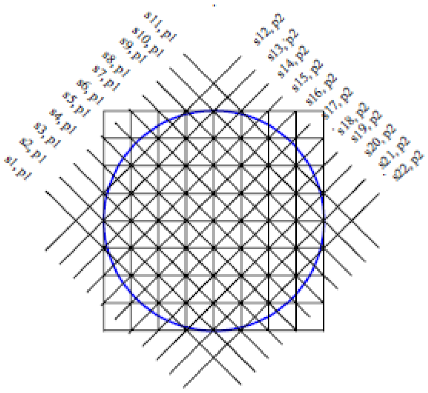


Figure 2(b). Rectilinear projection

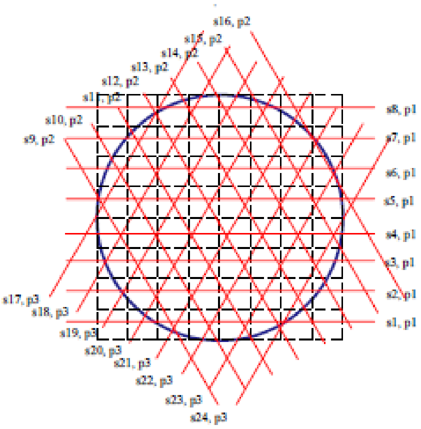


Figure 2(c). A combination of two orthogonal

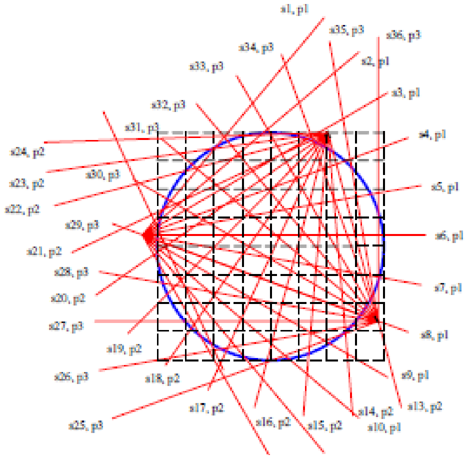


Figure 2(d). Three fan-beam projections and two rectilinear projections

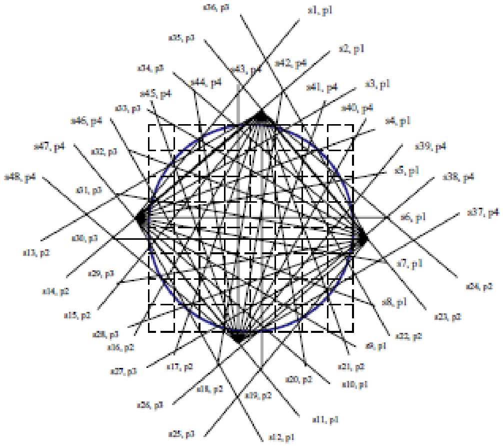


Figure 2(e). Four fan-beam projections

From all types of projections mentioned above, parallel beam projections have some disadvantages that could be concluded. Firstly, at least four projections are needed to obtain a good representation of solid particle flows. The reconstructed image will contain false copy of the solid particle flows when only two sets of parallel projections were employed due to aliasing problem. Aliasing problem as can be seen in figure 3 can be occur when two particles intercept the same view thus creating the ambiguity of the location of some particles [10]. It happens when two projections system are not enough to produce a good tomogram, and it produces insufficient information and lack of image resolution [10]. For that reason, more projection system can reduce such problems. Secondly, parallel beam projections required a large number of hardware. As a result, more components are required such as sensor jig and optical sensor to complete the system.

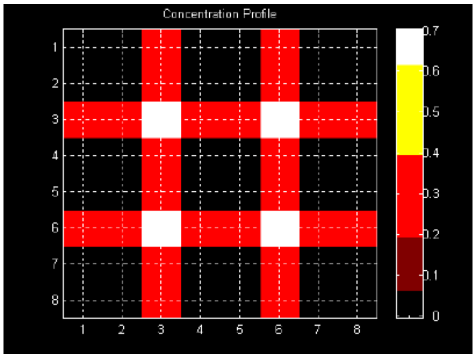


Figure 3. Aliasing problem: the actual and phantom objects are circled in green and blue, respectively

Fan beam projection is preferable for optical tomography since it can offer more number of measurement from the measurements transducer [15]. The fan beam projection is not concentrating to a straight line but focus on transmission angle [16]. The transmission angle can be known by looking to the data sheet of the transmitter where usually the angle value is notified. One light of the transmitter can be received by one or more receivers depend to the transmission angle as show in figure 4. The light of transmitter TX0 which has an angle of 30º will detect by receiver RX13, RX14, RX15, RX16, RX17 and RX18. It can be conclude that if the angle is increasing, the number of receiver detect the light also increasing. The Table 2 shows the types of projection and number of sensor that had used by previous research in the application optical tomography. From the table, we can see that there are significant differences in number of sensor used between parallel beam and fan beam projection technique. Fan beam required less number of sensors compared to parallel beam technique and the maximum numbers used for parallel beam is 156 sensors but only 64 sensors used for fan beam. Hence, the total cost of the project which applies the fan beam method can be reduced.

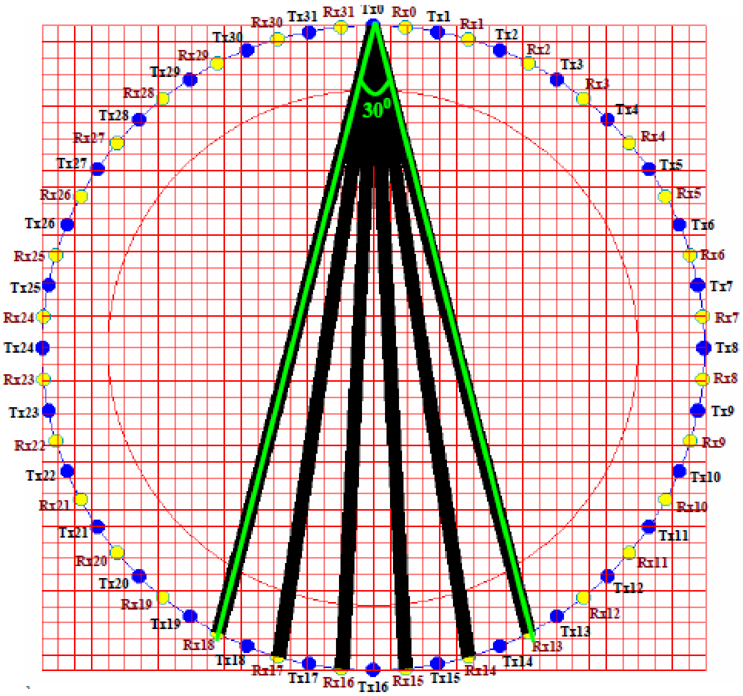


Figure 4. Fan beam projection

Table 2: Type of projection and number of sensors in previous researchers

Type of Projection	Number of Sensors	Reference
Parallel Beam	32	[9]
Parallel Beam	76	[10]
Fan Beam	16	[15]
Parallel Beam	156	[30]
Fan Beam	64	[20]
Parallel Beam	12	[29]
Parallel Beam	128	[18]
Fan Beam	4	[2]
Parallel Beam	156	[31]
Fan Beam	8	[19]
Parallel Beam	8	[25]
Fan Beam	16	[47]
Parallel Beam	32	[49]
Parallel Beam	156	[42]

The number of emitters and receivers are same for parallel beam projection while for fan beam projection it can be unequal [17]. As mentioned earlier, the tomography technique consists of several parts which are sensor, signal conditioning circuit, data acquisition system and image reconstruction. The emitter needs power supply to emit the light. For that reason, light projection circuit for switching the electronic signals is developed by Yunus and circuit using 555 timer which build on by Saad to switch ON the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) hence, the emitter will emit the light [18]-[19]. Chen had proved that the microcontroller chip can be also used to drive ON the emitter [20]. The example of transmitting circuit is shown in figure 5 [18]. The circuit consists of transistor ZTX689B, infrared LED SFH486P, resistor 33Ω and capacitor 10μF. The high pulse 5V signal and low pulse 0V produce by microcontroller are supply to base transistor to act as switch for transistor. A variable resistor, R_b is used to control the current flow in transistor base and R_c is used to protect the emitter from over current [15].

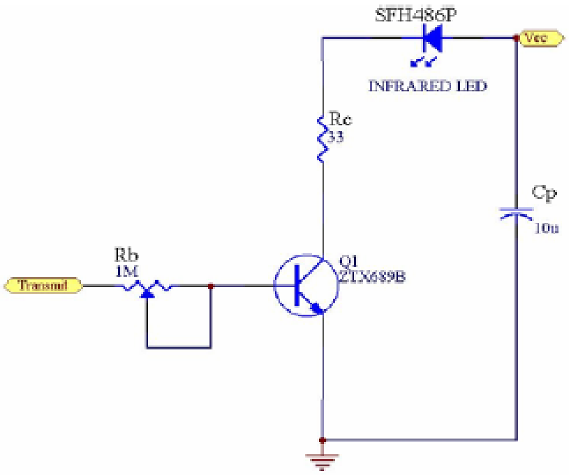


Figure 5. The transmitting circuit

The light is transmitted from the transmitter into the pipe to receiver. However, it is hard to place all the transmitters and emitters around and close to pipe, therefore, fiber optic is proposed to use in optical tomography. There are several advantages of fiber optic in process tomography [9],[18],[20]and [21]:

1) The transducer's performance are not affected due to fiber optic are more stable and immune to environment,
2) Electronic circuit is separated so that the process of troubleshoot the problems (if any) is easier to do,

3) Allow more sensors to place around the pipe since it required less space of place thus the resolution of tomogram can be upgrade,
4) The fiber optic does not invade the flow of process since it is mounted outside the pipe as shown in figure 6,
5) The system is immune to temperature, pressure, and viscosity of the fluid.

The optical fibers can be connected to the transmitters and receivers through the following steps [9]:

1) Some of the fiber optic cladding is removed as shown is figure 7(a).
2) 2 mm fiber optic without cladding is measured as shown in figure 7(b).
3) Exposed the end of fiber optic to candle for a few seconds until a convex surface is formed as shown in figure 7(c).

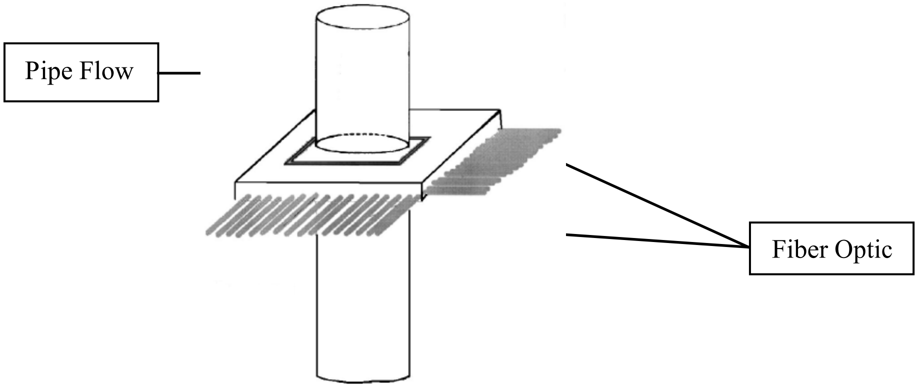


Figure 6. Optical fiber is mounted around the pipe

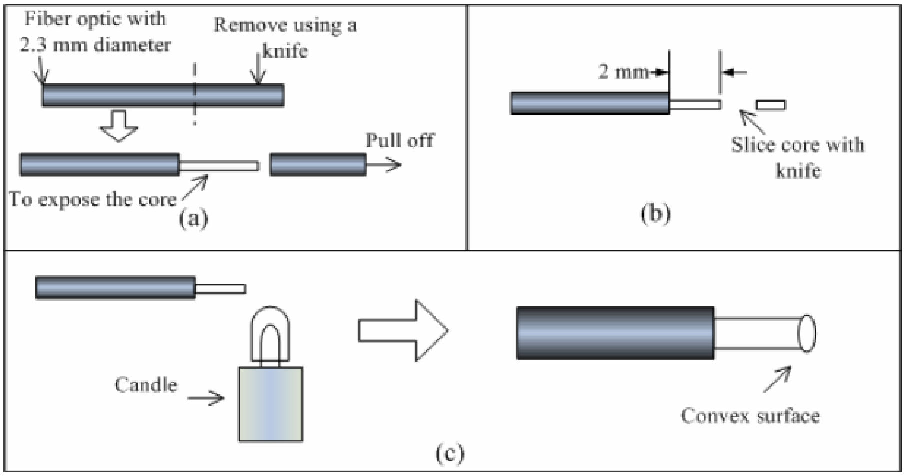


Figure 7. The fiber optic initial process

IV. CRITERIA FOR SENSOR SELECTION

The success in application of optical tomography is mostly depending to the selection of sensor [22]. Sensors in this technique include emitter and receiver and the criteria to consider are wavelength range, response time, and noise level. The emitter types that usually used are Light Emitting Diode (LED), infrared, laser and halogen bulb while for receiver transducer are photodiode, phototransistor and photomultipliers [17]. There are two types of light to consider in selecting the emitter, which are visible light and invisible light. For visible light, the wavelength of the light is equal to the light produce by the lamp in surrounding which is 380-750nm. While for invisible light, the wavelength is near to 700-1000nm and make the light of emitter faster to propagate to the receiver [17]. In selecting the receiver, the wavelength of the receiver should equal or near to the wavelength of emitter. Photodiodes are commonly used as the receiver while visible light can be used as the source. In addition, most photodiode is designed in wavelength of visible light's range. So, the photodiode is commonly selected by many researchers in optical tomography project.

V. MEASUREMENT SYSTEM

The measurement system consists of signal conditioning circuit, Digital Timing and Control Unit, and Data Acquisition System (DAS). The next subsections will discuss these components briefly.

a. Signal conditioning circuit

When the light from the transmitter propagate, the light is received by the receiver. All the light should be fully received by the receiver. Therefore, the measurement unit should be designed properly in order to make sure the signal from receiver can be process by the signal conditioning circuit. In the signal conditioning circuit, there are several stages that could be identified. The first stage is the current to voltage converter where the light received by receiver will convert to current as shown in figure 8. Then, the current will be converted to voltage parameter. The second stage is amplifier circuit, as illustrated in figure 9 where in this stage, the signal from the first stage will be amplified. The third and fourth stages are low pass filter circuit and buffer circuit, respectively as shown in figure 10.

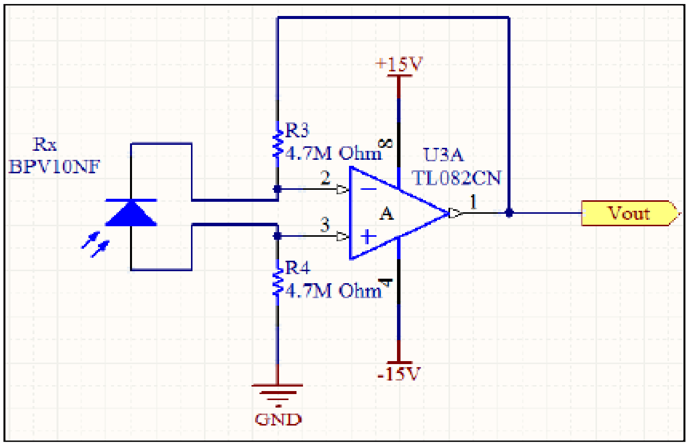


Figure 8. First stage: Current to voltage converter

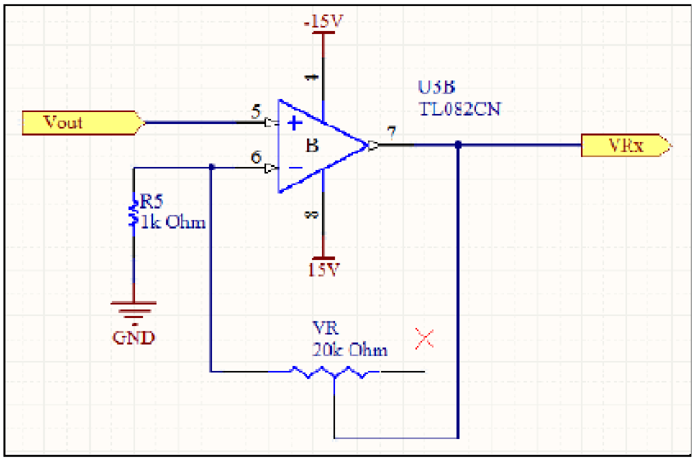


Figure 9. Second stage: Amplifier

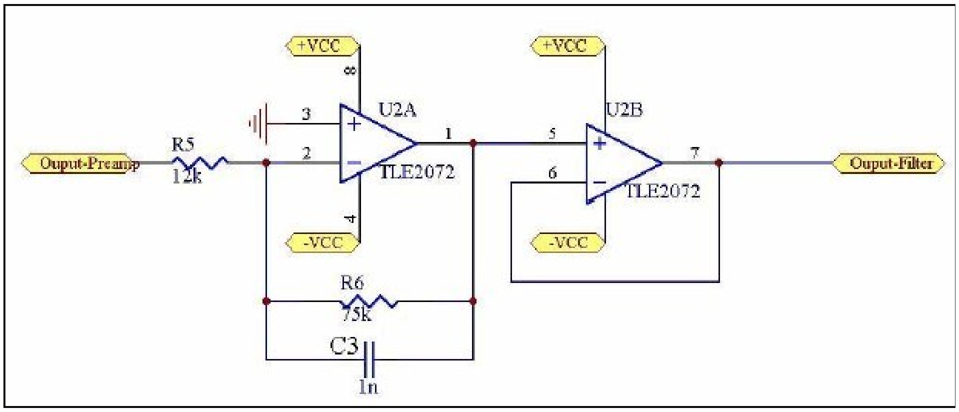


Figure 10. Third and fourth stage: Low pass filter and buffer circuit

b. Digital timing and control unit

The main purpose of the digital timing and control unit is to control the parameter used in the system where the parameters are frequency, sequence of projection and the time of the transmitter to on and off [23]. The other purpose is control the duration of data sampling performance in order to synchronize the operation of data acquisition system (DAQ) [18]. Leong in 2004 has designed the circuit where the signals consist of *Clk*, *Trig*, *BClk*, *LED_On* and light projection sequence as shown in figure 11. The signal is generated by Peripheral Interface Controller (PIC) Microcontroller.

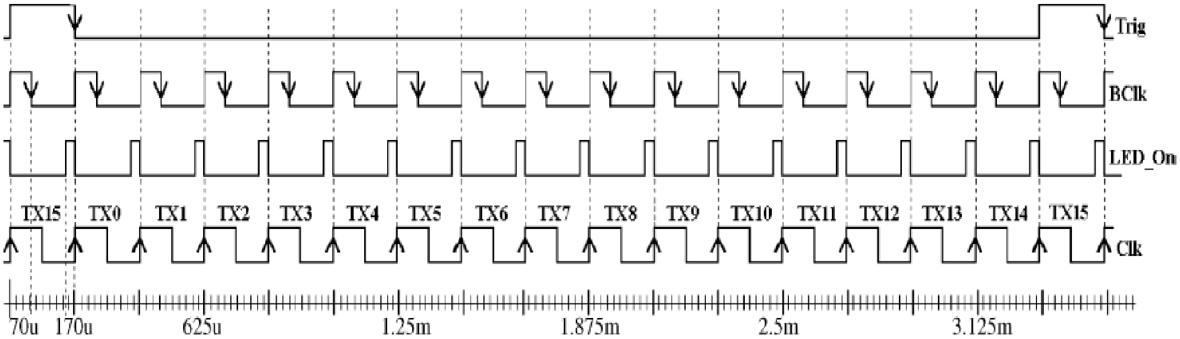


Figure 11. Digital timing and control signals

c. Data acquisition system (DAS)

The signal from the output of overall signal conditioning circuit will be process by data acquisition system (DAS). DAS is the process of sampling signals that can measure real world physical conditions and convert the resulting samples into digital numeric values that can be manipulated by a computer as illustrate by figure 12 [24]. Through DAS, the image processing in the pipeline or conveyor can be constructed on a computer or a laptop by using suitable image algorithms. The numbers of sensors used in process tomography almost depend to the channel of DAS. For example, if DAS have maximum 32 channels, the maximum number of sensors that can be used also 32 sensors. The speed of DAS is an important part that should be noted when buying the DAS. For real time purpose, the DAS should have high speed in data processing system in order to make the process tomography is reliable.

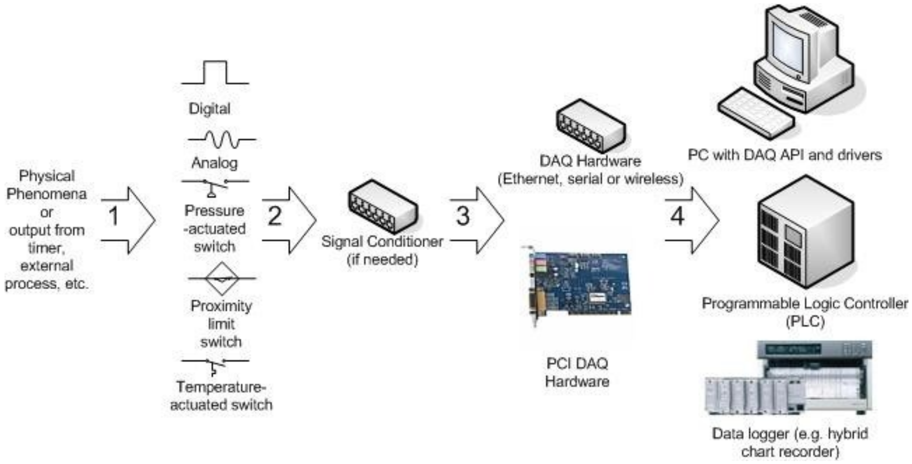


Figure 12. The system flow related to data acquisition system

V. IMAGE RECONSTRUCTION ALGORITHM

The reconstructed image from various tomographic sensing system may contain vital information of parameters in the cross-sectional of pipelines or conveyor [1]. The parameters can be the multiphase flow imaging, fluidized bed imaging and bubbles flow. This section will discuss three common algorithms that have been used in optical tomography which are Linear Back Projection (LBP), Filtered Back Projection, Layergram Back Projection and Hybrid Reconstruction Algorithm.

a. Linear Back Projection algorithm (LBP)

The algorithm is required to produce the image in the vessel or pipeline through the computer. There are many algorithms that can be applied in industrial process tomography where the algorithm is come from medical tomography [25]. Linear Back Projection Algorithm (LBP) is commonly used because it is straightforward in terms of the concept as compared to other algorithms [26]. The idea of the algorithm is all projection is back projected to its original direction as in figure 13, however, the disadvantage of LBP is the image produce is often blurred and out of shape [21]. In 1992, Dugdale et. al. [27] applied this algorithm to obtain the image inside the pipe. Abdul Rahim also had used this type of algorithm in his research where the concept of the algorithm is based on sensitivity maps [28]. Moreover, Mohamad used LBP to investigate the concentration profile of flame image by using 8 × 8 sensors pairs [29].

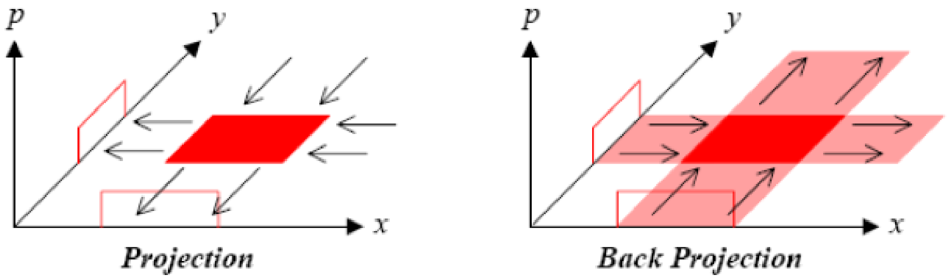


Figure 13. Back Projection

A research conducted by Ibrahim [10] proved that the concentration profile inside the vessel can be obtained by combining the voltage measured by each sensor with sensitivity map where the mathematical expression is

$$V_{ij} = \sum_{n=1}^{m} V_{sn} S_n \qquad (1)$$

Where V_{ij} is the voltage distribution in 8 × 8 matrix and V_{sn} is the voltage for nth sensor. S_n is sensitivity map for nth sensor and m is the total number of sensors mounted around the vessel.

b. Filtered Back Projection algorithm (FBP)

Filtered Back Projection Algorithm (FBP) is improvement LBP method. The algorithm has produced image better than LBP because it filtered the image construct by LBP by reducing the low frequency information. The algorithm is implementing by calculating the ratio of maximum value allowed in concentration matrix to each element in the full flow concentration matrix.

c. Layergram Back-Projection (LYGBP) and Hybrid reconstruction algorithm

Layergram back-projection (LYGBP) is another algorithm that can be used in process tomography. The algorithm was combined with hybrid reconstruction algorithm to reconstruct the images of the bubbles in the pipe [10]. The hybrid algorithm assumes binary values from the sensor, either zero for no material or one for the presence of material and constructs the image will look better than LBP. Pang [30] also used this algorithm to eliminate the ambiguous effect. This algorithm provides the some improvement of the tomogram where it actually based on LBP but some changes is made. The pixel is separate into five smaller parts where we can choose the parts whether it's included in the calculation of concentration or not. So, not all pixels are used in the calculation and by this way, the accurate image can be produced [31].

VI. APPLICATIONS

In the previous statement before, the tomography can be applied either in industrial or medical field. Each field has its own parameters that should be identified and measured. Hence, a single modality tomography is applied for that purpose but sometimes there are needs for some more sensing system since the data or result provide by a single modality are not enough. Thus, the addition sensing system is required to complete the task. This section will discuss the application of single modality and dual modality tomography's based on the previous researches. The velocity measurement process in single modality using optical sensor also included in this section.

a. Single modality tomography

Single modality tomography system can be said to be the earliest method that has been applied in industry. Single modality means that only one sensing technique is used for measurement purpose. Many optical tomography systems can be found for the application of process flow measurement. Rahim obtained the concentration profile for a plastic bead flow in conveyor using optical sensor [9]. His research had used optical fiber as the medium to transmit the light from halogen bulb to photodiode as receiver. Few years later, Ibrahim [10] measured the gas bubbles in vertical water column by using optical tomography. He had constructed the image of gas bubbles by using hybrid reconstruction algorithm where the experiment setup is illustrated in figure 14 which consists of pipe, bubbles outlet, pump and pressure meter. The concentration profile for the gas bubbles is shown in figure 15.

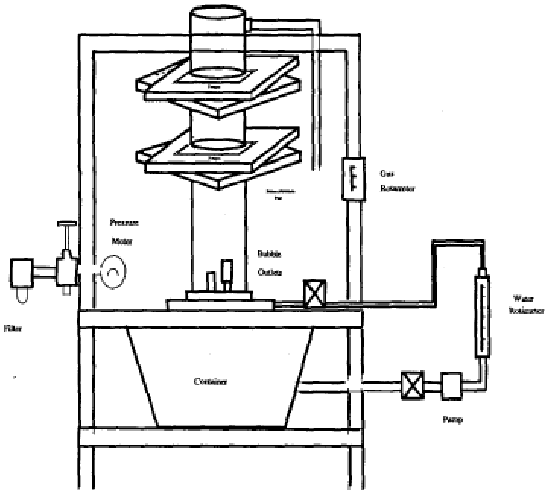


Figure 14. Experiment Setup for measuring gas bubbles flow rate

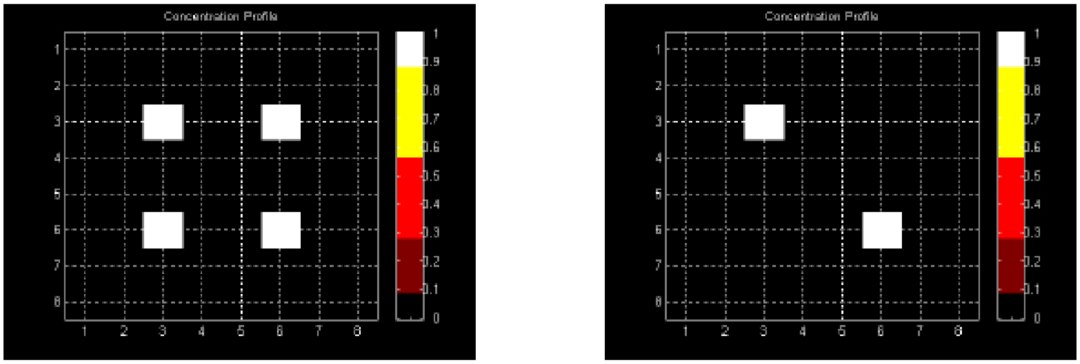


Figure 15. Concentration profile for gas bubbles using Hybrid reconstruction algorithm

Zheng et al [32] had investigated the concentration distribution and mass flow rate measurement for gravity chute conveyor in year 2006 in real time. They designed the multi-light sources and multi-light beam array to the pipeline with simulation in computer as illustrate in figure 16. The figure 17 shows four and 15 light sources are used where the four light sources have 15 beams, 15 light sources have 5 beams and 15 light sources have 15 beams. The apparatus of experiment consists of feeder hopper, motor, signal conditioning, laser diode and detector array and so on. Then, the reconstruct images from the experiments were compared with the simulation results**.**

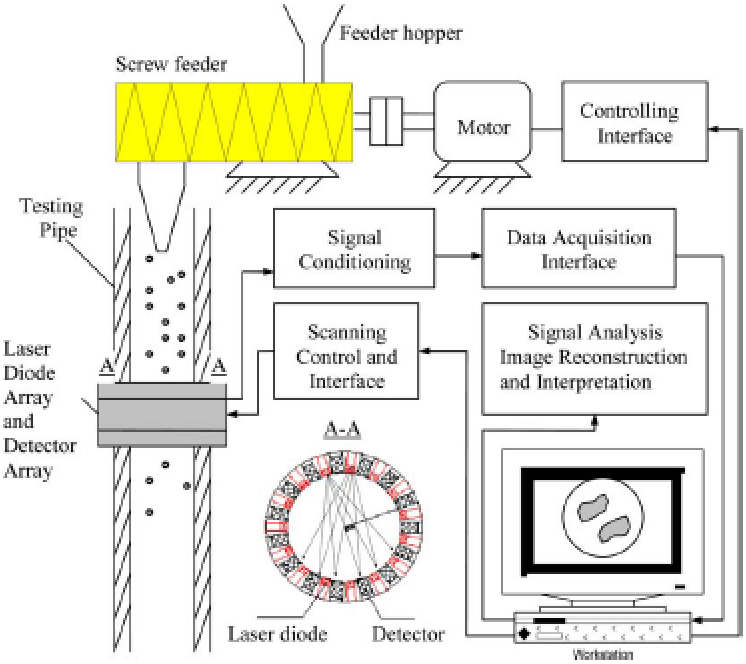


Figure 16. Experiment setup of Zheng et al [32]

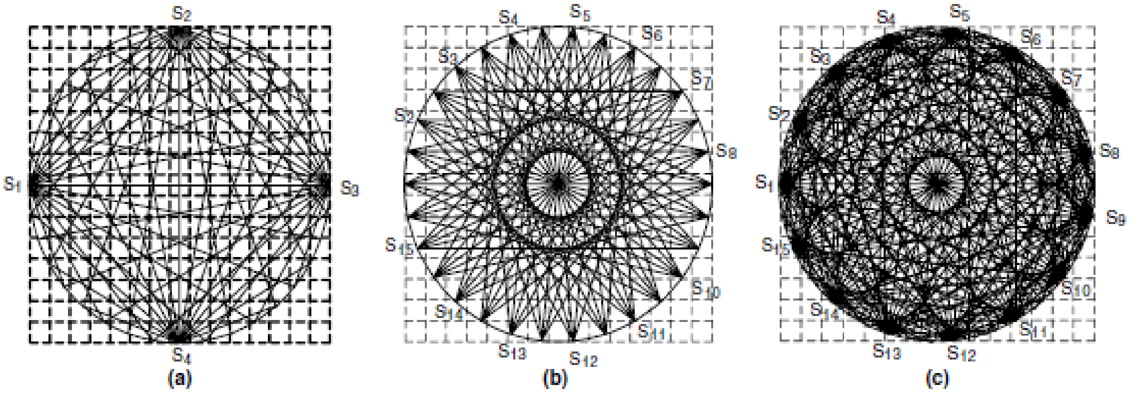


Figure 17. Fan shaped arrangements to different array structure. (a) 4 light sources, 15 beams; (b) 15 light sources, 5 beams; (c) 15 light sources, 15 beams [32]

Zheng et al [32] divided the experiments into two conditions; static and dynamic experiment. The static experiment used a pipe where transparent glass rods were inserted into the pipe and the images were obtained. The figure 18 shows the result of the static experiment.

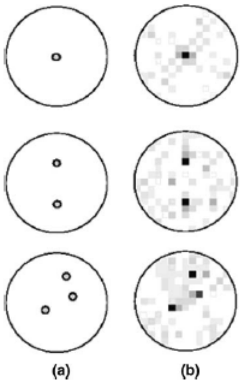


Figure 18. Reconstructed result of static experiment. (a) Original distribution (b) Reconstructed image [32]

In the dynamic experiment, silica sand was vertically poured down through the pipeline at a controlled rate. The measurement was done on-line, and the aim of the experiment was to estimate the concentration distribution from the reconstructed images, and to measure the mass flow rate at different screw feeder speed. The concentration profile for the silica sand is shown in figure 19 where the mass flow rate for the upper row is 6.1g/s, 22.2g/s for the middle and 33.9g/s for the lower image.

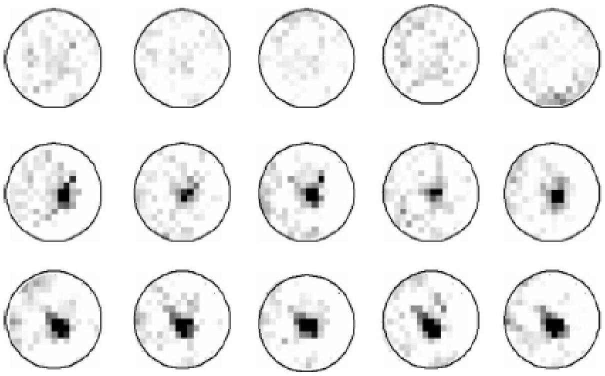


Figure 19. The concentration profile for different mass flow rate of silica sand (6.1g/s for upper row, 22.2g/s for the middle and 33.9g/s for the lower image.) [32]

Rzasa [33] employed the optical tomography for measuring aeration parameters in large water tanks. He focused on detection and definition of shapes of gas bubbles moving in a liquid where the column is exposed to homogeneous beam. The next ray is detected using optical waveguide detectors as shown in figure 20 [33].

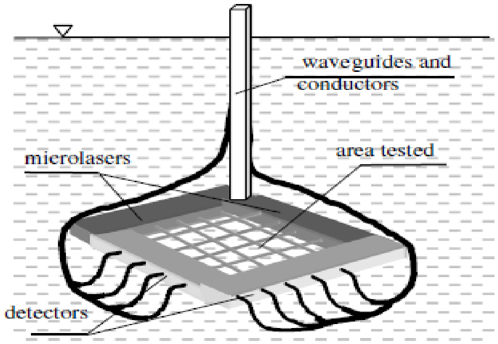


Figure 20. Structure of the measuring system [33]

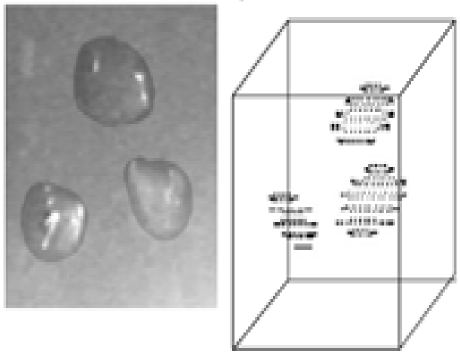


Figure 21. Group of bubbles in camera (left) the tomograph (right) [33]

The optical tomography technique can also be used to measure and analyze the velocity of particles flow in conveyor. The popular technique for the measurement is by using cross- correlation which was proposed by [34]. The technique is based on the deriving the transit time of particles or fluid flowing through a pair of sensors mounted upstream and downstream of the pipelines as shown in figure 22 [35]. The function of *x(t)* and *y(t)* is given by:

$$R(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t)y(t-\tau)dt \qquad (2)$$

Where $R(\tau)$ is the cross correlation function, $x(t)$ is the upstream sensor function and $y(t-\tau)$ is the downstream sensor function. In figure 22, the × box represents the function $x(t)y(t-\tau)$. The peak value in the equation (2) corresponds to the most probable time required for the flow travel from upstream to downstream sensors, τ_m. Then, the velocity can be calculated by divide the length between upstream and downstream sensors and peak time as equation (3).

$$V = \frac{L}{\tau_m} (m/s) \qquad (3)$$

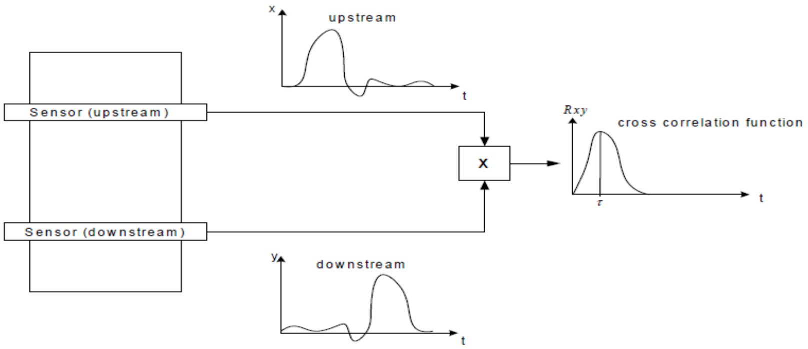


Figure 22. Cross-correlation method

Initially, the velocity measurement was measured using offline mode by [36] and [10]. Then, the online mode is implemented by Rahiman [37] and Chan [15] in order to make the measurements is more reliable and faster. Xie et al [38] identify the method of correlation divided into two types; Pixel to Pixel Correlation (PTP) and Sensor to Sensor Correlation (STS). PTP correlation method requires that images to be reconstructed first and this method requires the upstream and downstream concentration profiles [39]. Then, each pixel is taken from upstream sensor and will cross-correlate with the same pixel in downstream sensors in order to get the time delay. Hence, the velocity can be calculated using equation (3) where the distance between upstream and downstream sensor is divided by the time delay [40]. STS correlation is different from PTP correlation where the data from upstream sensor is correlated with downstream sensor instead of using pixels values [41]. The method is better than PTP correlation method since STS required only 2 × N times for N × N orthogonal sensor pairs for the number of cross correlation [42].The correlation techniques in [18],[30],[37] and [39] were used to measure the velocity of plastic beads flows in flow rigs while Ibrahim [10] measured the velocity of gas bubbles in a vertical column. Pang [30] has applied the data distribution system which consists of two personal computers (PC) in order to upgrade the speed of data processing time. Digital Signal Processor was implemented by [39] to replace Data Acquisition System (DAS) in performing data acquisition task hence; it can save the cost of the overall project. Furthermore, Tan [43] adopted the cross correlation method to measure the velocity of two phase flow; oil and water by using electrical resistance tomography while Lee [44] used electrodynamics sensor for measurement buck solid flow. In another scenario, Saad [19] performed the measurement of velocity for object flow by applying dual modality tomography based on optical and ultrasonic sensors.

b. Dual modality tomography

Dual modality tomography is a technique which uses at least two types of sensor for measurement purpose. The technique could be used as images comparison between the modalities. Furthermore, the images reconstructed from the different modalities can be used as an image. Most process flows only require a single modality process tomography since it enough to provide data and information, however, complex process flows may need additional type of tomography [45]. Rzasa [46] used optical and capacitance tomography as the sensors to measure two-phase gas-liquid flows in a horizontal conveyor. The test stand was designed to generate typical upward, downward and horizontal flows as figure 23. The system include 80mm diameter of pipe, measuring length 140cm, pump to supply water as label 2, temperature as label 6 and pressure meter as label 7. The gas supply system is a compressor labeled 8 which working pressure 0.05MPa.

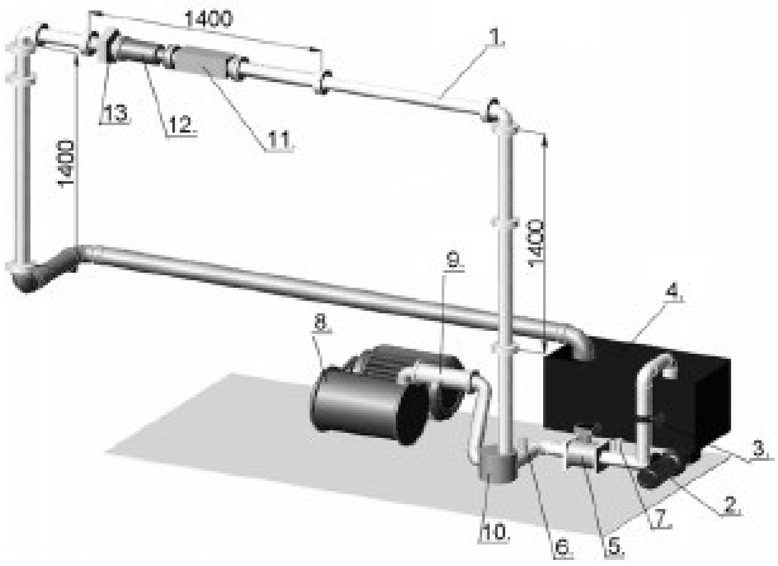


Figure 23. The test stands [46]

The capacitance tomography system is set up as figure 24 where the 16 capacitance sensors were installed around the pipe which have 76mm internal diameter. Meanwhile, the optical tomography system in figure 25 consists of five 55W light source as light transmitter, 64 phototransistors as light detector and 76mm diameter of pipeline. The light sources are located in five places in each side of pentagon’s corner.

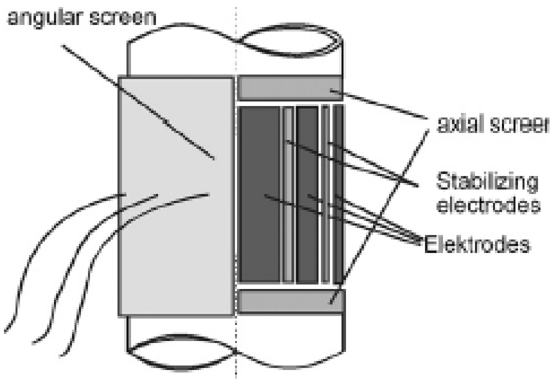


Figure 24. Capacitance tomography system

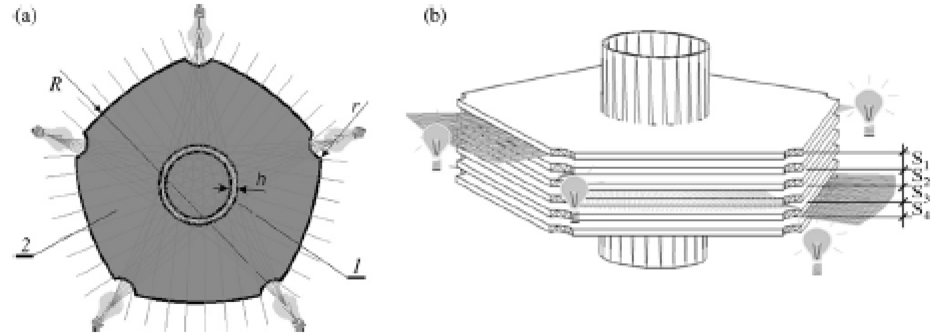


Figure 25. The optical tomography: (a) upfront view,(b) side view

The image reconstruction algorithms used in this research are Linear Back Projection (LBP) and Iterative Back Projection (IBP). Based from the result in figure 26, optical tomography constructed a good image for very small object but not for laminar structure. For the image of capacitive tomography in figure 27, it shows the method is more suitable to use to build images for laminar flows [46].

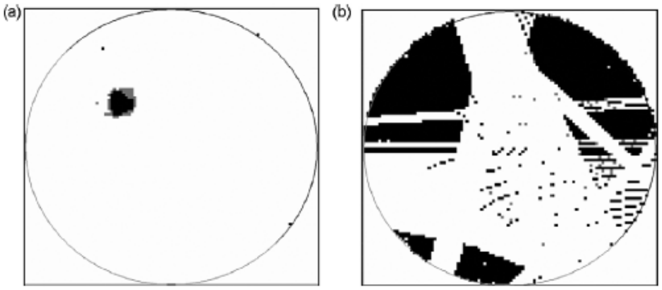
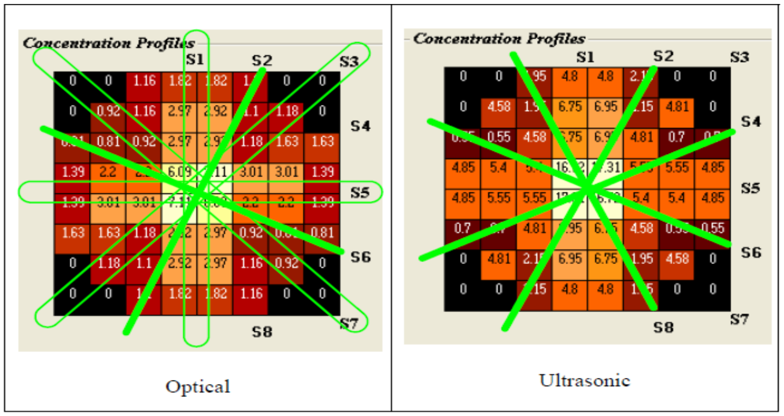


Figure 26. The image of optical tomography a) image of bubbles of 12mm, b) for a laminar flow

Mohd Zain [47] also used the same modality as Rzasa. In his research, every projection was vertically position for each measurement plane [48]. The tomography system used 16 pairs of optical sensors in a single plane and had 5 mm gap of distance between the sensors. In the final result showed that the better tomogram image has produced by using the dual types of sensors. Rohi [49] had used optical and electrodynamics sensor to obtain tomographic images solids of flow while optical and ultrasonic sensors were applied by Saad [19] in order to obtain the concentration profile and measure velocity of solid flows. Comparison of the concentration profile of 40mm diameter of round object between two sensors can be seen in figure 28. Moreover, the tomography technique also was applied in nuclear power industry where the gamma-ray and electrical capacitance tomography are used to monitor the waste separation process [50].



Optical

Ultrasonic

Figure 28. Optical and ultrasonic concentration profile

VII. TURBIDITY MEASUREMENT OF LIQUID

Turbidity is an optical quality and property of a liquid or sometimes describes as haziness of liquid medium such as water. In recent years, the uses of turbidity sensor to measure the water quality and suspended sediment concentration is increased significantly [51]. Turbidity measurement is commonly used light properties for analysis purpose since it will scatter away from straight lines path when the light is collided with particles [52]. The scattering value will be taken in investigating the turbidity measurement in certain liquid. For example, if the liquid is pure water, the scattering value is small since the light transmission is not effected much by the low intensity of the water but the scattering value is increasing if the water becomes darker or contaminated [52]. The turbidity sensors consist of many types but the common one is using light attenuation as it passes through a sample column of water. Bilro [50] and Niskanen [53] in their research had measured the water turbidity by using optical sensing based. Plastic Optical Fiber (POF) is applied in turbidity sensor to increase the accuracy and flexibility [54],[55]. Besides scattering, the turbidity of liquid samples can be analyzed based on the observation of transmission and reflection. Next section will discuss the formulation of optical attenuation model in turbidity measurement of liquid.

a. Optical attenuation model for turbidity measurement of liquid

In the optical attenuation model based on Beer-Lambert Law, the absorbance, *A* can be represented by the multiplication of absorption coefficient of the liquid medium, α with path length of light travel in the liquid medium, *l* [10] as denoted by the following equations,

$$A = \ln\left(\frac{V_m}{V_{in}}\right) = -\alpha\, l \qquad (4)$$

where *A* is the medium absorbance, V_m is the voltage of the receiving sensor (V) which proportional to the light intensity incident on the medium, I_o, V_{in} is the voltage of the receiver when there is no beam attenuation (empty pipe) (V) which proportional to the light intensity transmitted through the medium, *I*, *α is* the absorption coefficient of the liquid medium (mm^{-1}) and *l* is the path length of liquid medium (mm^{-1}).

Equation 4 can be rearranged into,

$$V_m = V_{in} \exp\left(-\alpha\, l\right) \qquad (5)$$

For a liquid medium that contains several different absorbing compounds, i.e. α_1, α_2, α_3….α_n the overall absorbance is the sum of the contribution of each compound which expands Equation. (5) into,

$$V_m = V_{in} \exp\left(-\alpha_1\, l_1 - \alpha_2\, l_2 - \alpha_3\, l_3 .... - \alpha_n\, l_n\right) \qquad (6)$$

where $\alpha_{1,2,3\,\text{to}\,n}$ is the absorption coefficient of compound *1* to compound *n* in the liquid medium (mm^{-1}) and $l_{1,2,3\,\text{to}\,n}$ is the path length of compound *1* to compound *n* in the liquid medium (mm^{-1}).

Since the mean absorption coefficient of the medium, α has a direct relationship with the turbidity of the liquid. Therefore, the main objective is to estimate the mean absorption coefficient of the medium, α. Next section will discuss the implementation of independent component analysis and tomography for the estimation of liquid turbidity.

b. Independent Component Analysis (ICA)

ICA is a technique for conversion of multidimensional vectors into components that are statistically as independent from each other as possible [56]. It was developed in the 1990s [57]-[58] since then, this analysis method has served as a tool in separating independent sources variables from a linear mixture which is widely used in many fields of applied science and engineering such as biomedical [59], image processing [60] and face recognition [61]. Moreover, ICA had been used for process separation of gas-liquid through electrical resistance tomography done by Xu et al [62]. The analysis can be model as,

$$X = AS \qquad (7)$$

where X is an $n \times m$ matrix that denotes n measured signals and comprising m variables, A is an $n \times d$ mixing matrix, and S is a $d \times m$ matrix denoting source signals [63]. Finding the mixing matrix A and/or source signal S is the aim of using ICA with assumptions that the components are mutually statistically independent with each other and also independent with noise components [56]. Define $W = A^{-1}$, so that,

$$\hat{S} = WX = A^{-1}AS = S \qquad (8)$$

ICA consists of many types of algorithm which are FastICA, Infomax ICA, Joint Approximate Diagonalization of Eigenmatrices (JADE), Mean-field ICA (MF-ICA), and Kernel ICA (KICA). In this paper only the FastICA and Infomax ICA will be discuss.

b.i FastICA

FastICA is based on a fixed-point iteration scheme for finding a maximum of the non-Gaussianity of components sequentially using deflation scheme where the algorithm is as follows [63]:

1) Choose an initial weight vector, w,
2) Let

$$w^{+} = E\{xg(w^{T}x)\} - E\{g'(w^{T}x)\}w \qquad (9)$$

In this equation, g is the derivative of non-quadratic function G that is used in the contrast function for solving ICA problem,

3) Let

$$w = w^{+} / \| w^{+} \| \qquad (10)$$

4) If not converged, go back to (8).

b.ii Infomax ICA

Infomax principle is based on the maximizing the information transferred in a network of nonlinear units. It is better to use since it provides noise reduction and global estimation [64]. The entropy of $z = g(y) = g(Bx)$ where $[g(y)]_i = g_i(y_i)$, $(1 \le i \le d)$ is a component-wise non-linear function. Hence, the contrast function is: $ø_1(B) = H(g(Bx)) = -K(Bx \,||\, \tilde{s})$ where H(·) = denotes differential entropy [63].

c. Turbidity measurement based on ICA and optical tomography

This section will discuss how independent component analysis (ICA) can serve as estimation tool of liquid turbidity. The new method of turbidity measurement is proposed in this paper. The scope of the study will involve developing a novel approach to estimate liquid material turbidity with air-bubble flow based on optical tomography system and using independent component analysis (ICA) method. The project will consist of 16 pairs of transmitters and receivers where the infrared LED will be used as transmitter and photodiode as receivers. The fan beam mode projection will be employed. Water samples in a water column made from vertical pipe will be mixed in order to change the turbidity level of the water sample. The weight of the clay will be increased to obtain different level of turbidity. Data Acquisition System (DAS) will be used to convert the signal from analog to digital where the user interface will be based on *LabView* software. Next, Independent Component Analysis (ICA) method will be employed to analyze the data to obtain the absorption coefficient (α) which has a relationship with the turbidity of the water that will be determined. In addition, the study will also focus on other liquid material such as oil and the relationship between the oil turbidity with percentage of fat content will be determined. The concentration profile can be obtained using back projection algorithm to estimate the air-bubble flow in liquid material with varying turbidity level. Previous research by Xu et al [62] proved that the data from process tomography can be synchronize to ICA method. Thus, it is expected that the system will be able to provide various information on the flow inside a pipe. Among the information that can be obtained from the system are the turbidity and concentration profile. Such information can provide vital clues on the process and can be beneficial to process industries in improving the efficiency of their plant.

VIII. CONCLUSION

As a conclusion, this paper provides an overview of the optical tomography which use and applied in industrial process plus the new method propose in turbidity measurement. Firstly it discussed the concept of tomography and the main design components of optical tomography. Then, it reviewed the latest research on process flow monitoring using various types of process tomography systems. Finally, the optical tomography concept has been used in the formulation of optical attenuation model in turbidity measurement of liquid based on independent component analysis (ICA). It is expected this method will greatly help scientists or engineers to obtain spatial attenuation of liquid instead of single point attenuation value which averaged the turbidity level of the liquid. This will enhance the measurement accuracy of the liquid turbidity level. On top of that, the design of optical tomography technique should be based on the main purpose of the project since we need to include the cost factor. Moreover, careful design process considering all the factors discussed above will avoid waste of money and system malfunctions.

REFERENCES

[1] R. A. Williams and M. S. Beck, Process tomography: principles, techniques, and applications. Butterworth-Heinemann Ltd, 1995, p. 624.

[2] M. Tajjudin, “Fan Beam Optical Tomography,” Master Thesis, Universiti Teknologi Malaysia, 2005.

[3] I. Ismail, J. C. Gamio, S. F. A. Bukhari, and W. Q. Yang, “Tomography for multi-phase flow measurement in the oil industry,” Flow Measurement and Instrumentation, vol. 16, pp. 145-155, 2005.

[4] M. A. Bennett, R. M. West, S. P. Luke, and R. A. Williams, “The investigation of bubble column and foam processes using electrical capacitance tomography,” Minerals Engineering, vol. 15, pp. 225-234, 2002.

[5] R. Abdul Rahim, Optical Tomography: Principles, Techniques, and Applications. Johor Bahru: Penerbit UTM, 2011.

[6] “Process Tomography Web Page,” University of Bergen, 1997. .

[7] S. Z. Mohd Muji, R. Abdul Rahim, M. H. Fazalul Rahiman, Z. Zakaria, E. J. Mohamad, and M. S. Karis, “The Linearity of Optical Tomography: Sensor Model and Experimental Verification,” Sensors & Transducers, vol. 132, no. 9, pp. 40-46, 2011.

[8] T. Froystein, “Gamma-ray Flow Imaging,” Proc. ECAPT 1993, Karlsruhe, Germany, pp. 213-216.

[9] R. Abdul Rahim, “A Tomography Imaging System for Pneumatic Conveyors using Optical Fibers,” Phd Thesis, Sheffield Hallam University, 1996.

[10] S. Ibrahim, “Measurement of Gas Bubbles in a Vertical Water Column using Optical Tomography.,” Phd Thesis, Sheffield Hallam University, 2000.

[11] M. A. Hashim, “Optical Process Tomography For Measurement of Bubbles,” Degree Thesis, Universiti Teknologi Malaysia, 2011.

[12] E. Schleicher, M. J. Silva, S. Thiele, A. Li, E. Wollrab, and U. Hampel, “Design of an optical tomograph for the investigation of single- and two-phase pipe,” Meas. Sci. Technol, vol. 94006, no. 19, p. 14, 2008.

[13] C. Yan, J. Zhong, Y. Liao, S. Lai, M. Zhang, and D. Gao, “Design of an applied optical fiber process tomography system,” Sensors And Actuators, vol. 104, pp. 324-331, 2005.

[14] S. Ibrahim, R. G. Green, K. Dutton, K. Evans, R. A. Rahim, and A. Goude, “Optical sensor configurations for process tomography,” Meas. Sci. Technol, vol. 10, pp. 1079-1086, 1999.

[15] C. K. San, “Real Time Image Reconstruction For Fan Beam Optical Tomography System.,” Master Thesis, Universiti Teknologi Malaysia, 2002.

[16] R. A. Rahim, L. C. Leong, K. S. Chan, S. Sulaiman, and J. F. Pang, “Tomographic Imaging: Multiple Fan Beam Projection Technique Using Optical Fibre Sensors,” Computers, Communications, & Signal Processing with Special Track on Biomedical Engineering, 2005. CCSP 2005. 1st International Conference on 14-16 Nov. 2005, pp. 115-119, 2005.

[17] R. A. Rahim, P. J. Fea, C. K. San, and M. H. Fazalul Rahiman, “Optical Tomography: Infrared Tomography Sensor Configuration Using 4 Parallel Beam Projections,” Sensors & Transducers, vol. 72, no. 10, pp. 761-768, 2006.

[18] M. A. Mohd Yunus, “Imaging Of Solid Flow In a Gravity Flow Rig Using Infra-Red Tomography,” Master Thesis, Universiti Teknologi Malaysia, 2005.

[19] M. S. Saad, "Concentration and Velocity Measurement of Flowing Objects Using Optical and Ultrasonic Tomography," Master Thesis, Universiti Teknologi Malaysia, 2007.

[20] L. L. Chen, "Implementation of Multiple Fan Beam Projection Technique in Optical Fibre Process Tomography," Master Thesis, Universiti Teknologi Malaysia, 2005.

[21] S. Ibrahim, R. G. Green, K. Dutton, and R. Abdul Rahim, "Lensed optical fiber sensors for on-line measurement of flow.," ISA transactions, vol. 41, no. 1, pp. 13-8, Jan. 2002.

[22] S. Z. Mohd Muji, M. Morsin, and R. Abdul Rahim, "Criteria for sensor selection in optical tomography," in 2009 IEEE Symposium on Industrial Electronics & Applications, 2009, no. Isiea, pp. 510-514.

[23] R. A. Rahim, K. S. Chan, J. F. Pang, and L. C. Leong, "A Hardware Development for Optical Tomography System using Switch Mode Fan Beam Projection," Sensors and Actuators A: Physical, vol. 120, no. 1, pp. 277-290, Apr. 2005.

[24] J. Park and S. Mackay, Data Acquisition for Instrumentation and control Systems. Newnes, 2003.

[25] M. M. Elmajri, "A Tomography Imaging System Using Two Types of Sensor," Master Thesis, Universiti Teknologi Malaysia, 2008.

[26] T. Dyakowski, L. F. C. Jeanmeure, and A. J. Jaworski, "Applications of electrical tomography for gas – solids and liquid – solids flows — a review," Powder Technology, vol. 112, pp. 174-192, 2000.

[27] P. Dugdale, R. G. Green, A. J. Hartley, R. Jackson, and J. Landauro, "Optical sensors for process tomography," ECAPT 1992, Process Tomography: A Strategy for Industrial Exploitation, European Concerted Action on Process Tomography, Manchester, United Kingdom.

[28] R. G. Green, R. Abdul Rahim, K. Evans, F. J. Dickin, B. D. Naylor, and T. P. Pridmore, "Concentration profiles in a gravity chute conveyor by optical tomography measurement," Powder Technology, vol. 95, no. 1, pp. 49-54, Jan. 1998.

[29] E. J. Mohamad, "Flame Imaging using Laser Based Transmission Tomography," Master Thesis, Universiti Teknologi Malaysia, 2005.

[30] P. Jon Fea, "Real-Time Velocity And Mass Flow Rate Measurement Using Optical Tomography.," Master Thesis, Universiti Teknologi Malaysia, 2004.

[31] R. A. Rahim, C. K. Thiam, M. Hafiz, and F. Rahiman, "An Optical Tomography System Using a Digital Signal Processor," Sensors, vol. 8, pp. 2082-2103, 2008.

[32] Y. Zheng and Q. Liu, "Investigation on concentration distribution and mass flow rate measurement for gravity chute conveyor by optical tomography system," Measurement, vol. 39, pp. 643-654, 2006.

[33] M. R. Rzasa and A. Plaskowski, "Application of optical tomography for measurements of aeration parameters in large water tanks," Meas. Sci. Technol, no. 14, pp. 199-204, 2003.

[34] M. . Beck, R. . Green, and " R. Thorn, "Non-intrusive Measurement of Solid Mass Flow in pneumatic conveying," J.Phys. E:Sci.Instrum., vol. 20, no. 7, pp. 835-840.

[35] M. S. Beck and A. Plaskowski, "Cross Correlation Flowmeters: Their Design and Application," IOP Publishing Ltd, p. 240, 1987.

[36] M. F. Rahmat, "Instrumentation of Particle Conveying Using Electrical Charge Tomography," Phd Thesis, Sheffield Hallam University, 1996.

[37] M. H. Fazalul Rahiman, "Real Time Velocity Profile Generation of Powder Conveying Using Electrical Charge Tomography," Master Thesis, Universiti Teknologi Malaysia, 2002.

[38] G. C. Xie, A. L. Stott, S. M. Huang, A. Plaskowski, and M. S. Beck, "Mass-flow Measurement Of Solids Using Electrodynamics and Capacitance Transducers.," J. Phys. E:Sci. Instrum, vol. 22, no. 9, pp. 712-719, 1989.

[39] R. A. Rahim, K. T. Chiam, M. H. F. Rahiman, and " P. Jayasuman, "Velocity Profile Measurement Using Digital Signal Processor-Based Optical Tomography System," IEEE Sensors Journal, vol. 9, no. 9, pp. 1076-1083, 2009.

[40] R. Abdul Rahim, P. J. Fea, and C. K. San, "Optical tomography: real-time velocity profile measurement using pixel-to-pixel and sensor-to-sensor method," Optical Engineering, vol. 45, no. 3, p. 033604, 2006.

[41] S.Ibrahim, R.G.Green, K.Evans, K. Dutton, and R. A. Rahim, "Optical Tomography for process measurement and control," in Proc. Control UKACC Int. Conf Sept 4-7, 2000,, pp. 188-190.

[42] R. Abdul Rahim, Y. Mohd Yunos, M. H. Fazalul Rahiman, S. Z. Mohd Muji, C. Kok Thiam, and H. Abdul Rahim, "Optical tomography: Velocity profile measurement using orthogonal and rectilinear arrangements," Flow Measurement and Instrumentation, vol. 23, no. 1, pp. 49-55, Mar. 2012.

[43] C. Tan and F. Dong, "Cross Correlation Velocity of Oil-water Two-Phase Flow by a Dual-Plane Electrical Resistance Tomography System," IEEE, 2010.

[44] W.L. Yaw, "Real-Time Mass Flow Rate Measurement for Bulk Solid Flow Using Electrodynamic Tomography System," Master Thesis, Universiti Teknologi Malaysia, 2007.

[45] C. Qiu, B. S. Hoyle, and F. J. W. Podd, "Engineering and application of a dual-modality process tomography system," Flow Measurement and Instrumentation, vol. 18, pp. 247-254, 2007.

[46] M.R.Rzasa, "The measuring method for tests of horizontal two-phase gas–liquid flows, using optical and capacitance tomography.," Nuclear Engineering and Design,, vol. 239, no. 4, pp. 699-707, 2009.

[47] R. Mohd Zain, "The Development Of A Dual Modality Tomography (DMT) System Using Optical And Capacitance Sensors For Solid/Gas Flow Measurement," Master Thesis, Universiti Teknologi Malaysia, 2009.

[48] S. Z. M. Muji et al., "Optical Tomography: A Review On Sensor Array, Projection Arrangement and Image Reconstruction Algorithm," International Journal of Innovative Computing, Information and Control, vol. 7, no. 7, pp. 1-17, 2011.

[49] N. Mohammad Rohi, "Dual modality tomography system using optical and electrodynamic sensors to obtain tomographic images of solid flow," Master Thesis, Universiti Teknologi Malaysia, 2009.

[50] B. A. Cattle and R. M. West, "A two-dimensional dual-modality tomography technique for a radioactive waste separation process," Annals of Nuclear Energy, vol. 33, pp. 1236-1244, 2006.

[51] L. Bilro, S. A. Prats, J. L. Pinto, J. J. Keizer, and R. N. Nogueira, "Design and performance assessment of a plastic optical fibre-based sensor for measuring water turbidity," Measurement Science and Technology, vol. 21, no. 10, p. 107001, Oct. 2010.

[52] A. F. B. Omar and M. Z. B. Matjafri, "Turbidimeter design and analysis: A review on optical fiber sensors for the measurement of water turbidity," Sensors, vol. 9, no. 10, pp. 8311-8335, Jan. 2009.

[53] I. Niskanen, J. Räty, and K.-E. Peiponen, "A multifunction spectrophotometer for measurement of optical properties of transparent and turbid liquids," Measurement Science and Technology, vol. 17, no. 12, p. N87-N91, Dec. 2006.

[54] P. Aiestaran, J. Arrue, and J. Zubia, “Design of a Sensor Based on Plastic Optical Fibre (POF) to Measure Fluid Flow and Turbidity,” Sensors, vol. 9, pp. 3790-3800, 2009.

[55] M. Borecki, “Intelligent Fiber Optic Sensor for Estimating the Concentration of a Mixture-Design and Working Principle,” Sensors, pp. 384-399, 2007.

[56] P.Comon, “Independent component analysis: A new concept?,” Signal Process, vol. 36, no. 3, pp. 11-20, 1994.

[57] C. Jutten and J. Herault, “Blind separation of sources, Part 1: An adaptive algorithm based on neuromimetic architecture,” Signal Processing, vol. 24, pp. 1-10, 1991.

[58] N. Delfosse and P. Loubaton, “Adaptive Separation of Independent Sources: A Deflation Approach,” Signal Processing, vol. 45, pp. 59-83, 1995.

[59] C. J. James and C. W. Hesse, “Independent component analysis for biomedical signals (Topical review),” Pysical. Meas., vol. 26, no. 1, p. R15-R39, 2005.

[60] N. Katsumata and Y. Matsuyama, “Database retrieval for similar images using ICA and PCA bases,” Eng. Appl. Artif. Intell., vol. 18, no. 6, pp. 705-717, 2005.

[61] P. C. Yuen and J. H. Lai, “Face representation using indepedent component analysis,” Pattern Recognit., vol. 35, no. 6, pp. 1247-1257, 2002.

[62] Y. Xu, H. Wang, Z. Cui, F. Dong, and Y. Yan, “Separation of Gas-Liquid Two-Phase Flow Through Independent Component Analysis,” IEEE Instrumentation And Measurement, vol. 59, no. 5, pp. 1294-1302, 2010.

[63] G. Wang, Q. Ding, and Z. Hou, “Independent component analysis and its applications in signal processing for analytical chemistry,” Trends in Analytical Chemistry, vol. 27, no. 4, pp. 368-376, 2008.

[64] F. Esposito et al., “Spatial independent component analysisof fuctional MRI time-series: To what extent do result depend on algorithm used?,” Hum. Brain Mapp., vol. 16, no. 3, pp. 146-157, 2002.