Optical Fibres For Process Tomography: A Design Study

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Abstract *-- This paper describes modelling of optical fibre sensing arrays aimed at optimising the design of the tomography system being built by the authors. Two forms of optical sensing are considered; one relating to optical attenuation due to material with differing optical densities, the second to 'optical path length', which is used for opaque solids in air or liquid. The circular flow pipe is mapped onto an eight by eight rectangular array of pixels. Four flow models are investigated: a single pixel flow, two pixels flow, half flow and full flow models. Different arrangements of the fibre sensors are considered for various projections. The forward problem is solved for all combinations of flow model and sensor arrangement. Back projection and filtered back projection are used to reconstruct the image. A modified reconstruction algorithm combining LBP and a priori knowledge is outlined. Numerical tests, based on the reconstruction, are used to identify the best system to be implemented in hardware.*

Keywords: Optical Fibres, Process Tomography, Models

1. INTRODUCTION

Direct analysis of the internal characteristics of process plant is vital in order to improve the design and operation of production and control equipment. In such applications, the measuring instruments must employ robust, non-intrusive sensors which can be used in aggressive and fast moving fluids and multi-phase mixtures [1].

Process tomography is a technique still in its infancy, but it has the potential for enabling great improvements in efficiency and safety in process industries, while minimising waste and pollution in a range of applications. It can be used to obtain both qualitative and quantitative data needed in modelling a multi-fluid flow system. In tomography, multiple projections are used to obtain sets of data from various views. The tomographic imaging of objects provides an opportunity to unravel the complexities of structure without invading the object.

The overall aim of this project is to investigate the use of tomographic measurement for on-line monitoring of particles and droplets having low concentration being conveyed by a fluid. A typical example is the measurement of crude oil being discharged by tankers flushing their oil storage tanks. This project aims to combine the sensitivity of optical sensors with the area monitoring potential of process tomography.

2. MATHEMATICAL MODELLING

Modelling is carried out to predict the spatial and temporal behaviour of a process and it becomes more significant as the inherent complexity of a process increases [2].

In practical systems, several projections are needed to reduce aliasing which occurs when two particles intercept the same view [3].

The forward problem for the individual sensors is modelled, used to solve the inverse problem and derive the linear back projection and filtered back projection algorithms [4]. Modelling is carried out based on two parameters affecting the measured output of the sensor:-

(a) Path length of the sensing beam within the pipeline projections [5][6].

(b) Optical attenuation due to changes in optical density within the pipeline.

In previous projects, Ruzairi [5] concentrated on the path length method whereas Ramli [6] focused effort on the optical attenuation method. This project investigates both methods, which enables a comparison between their performance to be made.

2.1. Projection Geometry

Different arrangements of the fibre sensors are considered for different types of projections. These include :-

(a) two orthogonal projections consisting of several parallel views (Fig.1).

(b) two rectilinear projections consisting of several parallel views inclined at 45° to one another (Fig.2).

(c) a combination of two orthogonal and two rectilinear projections (Fig.3).

(d) three fan-beam projections (Fig.4).

(e) four fan-beam projections (Fig.5).

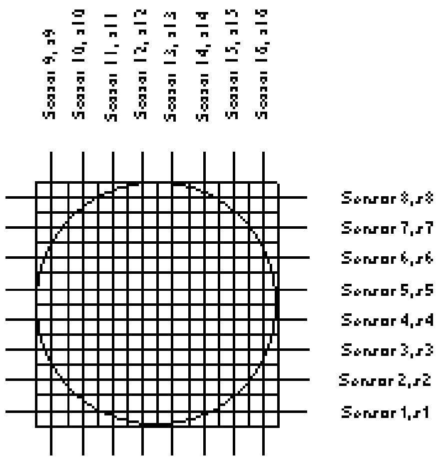

Figure 1 Orthogonal projections

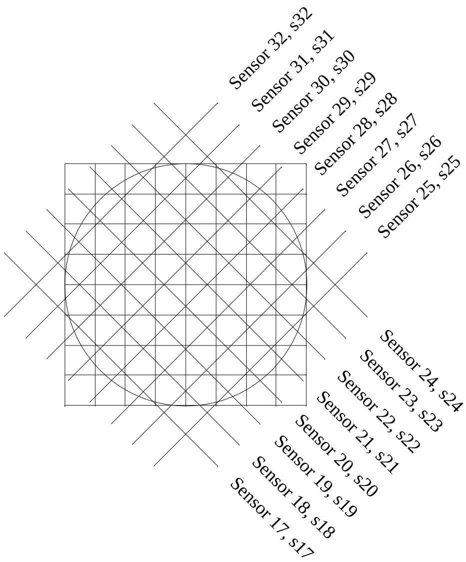

Figure 2 Rectilinear projections

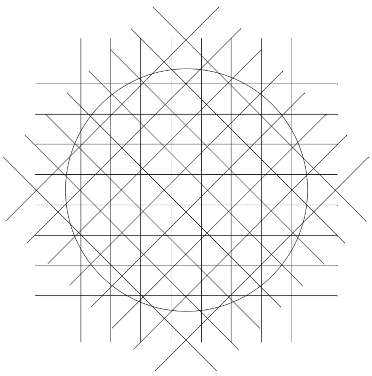

Figure 3 Combination of orthogonal and rectilinear projections

A series of angular projections of the light source and detector are used to interrogate the measurement section. These are termed fan beam projections.

In the case of three fan-beam projections, three light sources are used. Each light source will supply twelve light beams which are spaced at 10° degrees intervals. This results in the cross-section of the pipe being interrogated by a total of 36 light beams as shown in Figure 4.

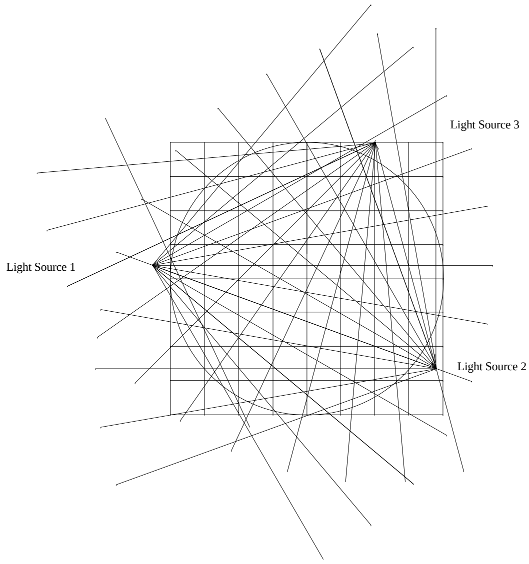

Figure 4 Three fan-beam projections

In the case of four fan-beam projections, four light sources are utilised and the projections are placed 90° apart as shown in Figure 5 resulting in a total of 48 light beams.

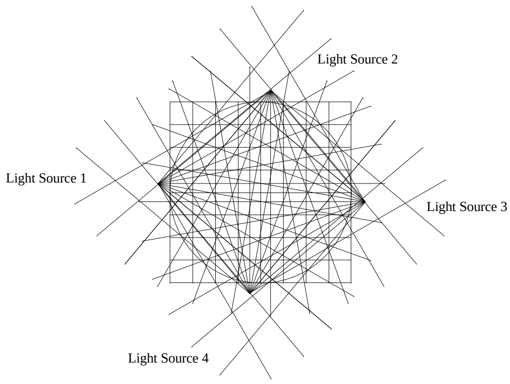

Figure 5 Four fan-beam projections

All the projection geometries are investigated for both the path length and the attenuation models.

3. PATH LENGTH MODEL

This model is based on the length of the optical sensing beam within the conveyor, the greater the active length, the greater the probability of a particle intercepting the beam [5].

3.1 Forward Problem for path length method

The forward problem provides the theoretical output of each sensor under no-flow and flow conditions when the sensing area is considered to be two dimensional. Solution of the forward problem generates a series of sensitivity matrices. Each matrix is associated with a specific sensor and relates to the sensor output under flow conditions.

To simplify the model, it is assumed that light beams travel in straight lines. It is assumed that for each light beam, the distance between emitter and detector is 100 mm and the beam width is 1 mm (i.e. the model neglects beam spread). It is also assumed that the beam in each pixel has a rectangular shape which simplifies the calculation of the area of the light beam in each pixel. Each pixel is designated as P_{ij} ,where i is the row number and j is the column number. The dimension of each pixel is 10mm x 10mm.

The area of each pixel enclosed by the circle is calculated. Then the area occupied by a specific light beam in each pixel is determined. Pixels outside the circle (representing the flow pipe) and pixels through which the specified light beam does not pass are assumed to contain air. Based on this *a priori* knowledge all such pixels will be assigned zero sensitivity values [5]. The sensitivity matrix for each light beam (or for each sensor) is formed by calculating the ratio of the area of the light beam in each pixel to the area of the corresponding pixel. Each pixel is evaluated separately and the contribution from each pixel forms the sensitivity map [5]. Each sensor is considered separately.

3.2 Inverse Problem for the path length model

The inverse problem estimates the distribution of material within the pipe which provides the measured sensor outputs. Due to the limited number of projections (i.e. 36 for the three projection system) and the larger number of pixels inside the pipe (i.e. 60), an analytic solution is not possible, so linear back projection (LBP) is used to solve the inverse problem.

3.2.1 Linear Back Projection

In the linear back projection algorithm, the concentration profile is generated by combining the voltage reading from each sensor (measured data) with its computed sensitivity map. To reconstruct the image, each sensitivity map matrix is multiplied by its corresponding sensor reading. This results in n 8 x 8 matrices, where n is the number of projections. This process can be expressed mathematically as

$$V_{ij} = \sum_{n=1}^{n=36} V_{s_n} s_n \qquad (1)$$

where

V_{ij} = voltage distribution in 8 x 8 matrix

V_{s_n} = voltage for nth sensor

s_n = sensitivity map for nth sensor in the form of an 8 x 8 matrix.

The voltage distributions, V_{ij} should be converted to concentration values. However, this has not been done for this paper as it only requires rescaling.

The voltage distributions are available as matrices (useful for quantitative information) and pictorially. A commonly used technique to improve LBP images is to use a filter, resulting in Filtered Linear Back Projection. This was investigated in this work by adjusting the full flow LBP result so that all none zero values in the image were equal. Selected examples are shown in figures 6 - 11.

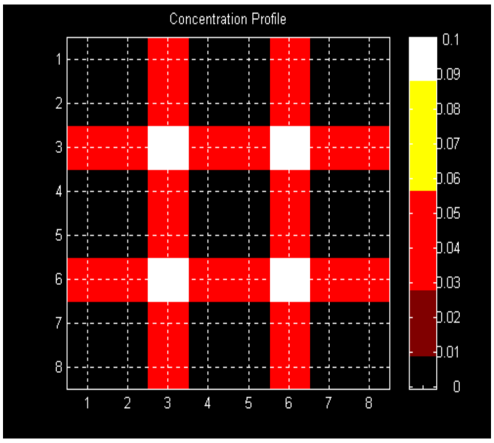

Figure 6 LBP for two orthogonal projections: two pixels flow model

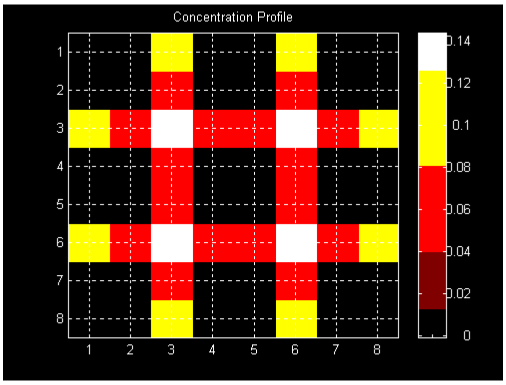

Figure 7 Filtered LBP for two orthogonal projections: two pixels flow model

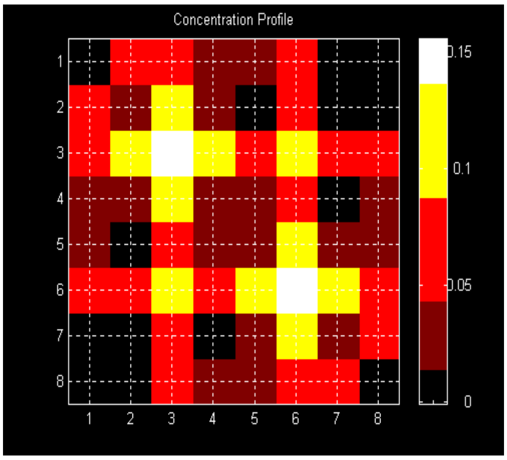

Figure 8 LBP for two orthogonal and two rectilinear projections: two pixels flow model

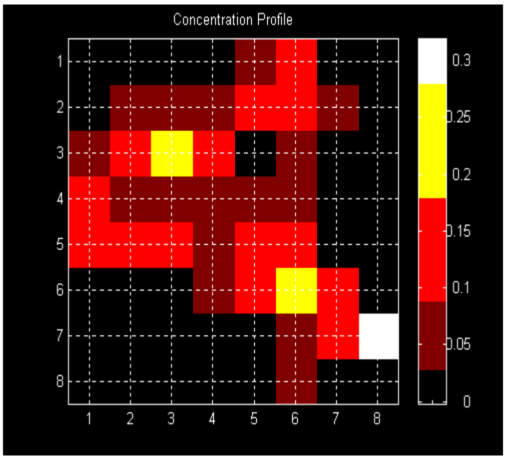

Figure 9 LBP for three fan beam projections: two pixels flow model

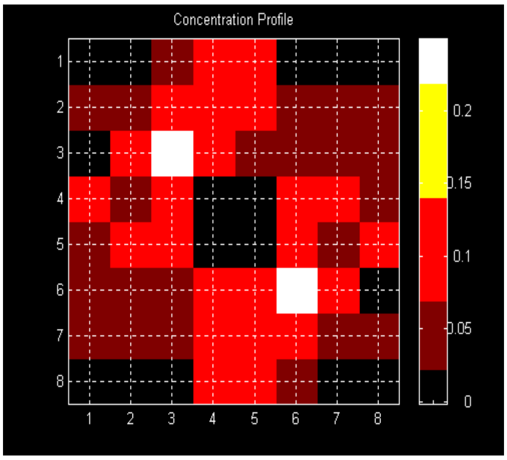

Figure 10 LBP for four fan beam projections: two pixels flow model

0	0	0	0	0.054	0.0995	0	0
0	0.076	0.0315	0.0814	0.1023	0.1023	0.0385	0
0.0691	0.1022	0.1975	0.1008	0.0025	0.0525	0.0025	0.0018
0.1781	0.0446	0.0395	0.0586	0.05	0.05	0	0
0.0949	0.105	0.1074	0.0754	0.0888	0.1125	0	0
0	0	0	0.0795	0.1131	0.2354	0.1215	0
0	0	0	0	0	0.0548	0.1512	0.3167
0	0	0	0	0	0.0538	0	0

Figure 11 Matrix representing the concentration profile for three fan beam projections: two pixels flow model

These results are discussed in section 5.

4. THE OPTICAL ATTENUATION MODEL

In this model the output value of the sensor is a function of the medium through which the light traverses coming from the emitter. This model neglects scattering and beam diversion. It is based on absorption of the beam by the medium within the pipe as shown in equation (2)

$$V_m = V_{in} \exp[\,(-\alpha_a \times l_a) + l_o(\alpha_a - \alpha_o)] \quad (2)$$

where:

V_m = voltage of the receiving sensor

V_{in} = voltage of the receiver when there is no beam attenuation

α_a = absorption coefficient of air

α_o = absorption coefficient of object

l_a = path length of air

l_o = path length of object

It is assumed that the attenuation coefficient of air, α_a = 0.0142 mm^{-1}[7] and the attenuation coefficient of the object, α_o = 0.05 mm^{-1} [6]. The output voltage for each sensor is calculated for each pixel in turn. This process is repeated until all pixels within the pipe have been considered. This process is also repeated for all the sensors resulting in n 8 x 8 matrices where n is the number of views. The linear back projection and filtered back projection calculations for the optical attenuation model are similar to the path length model (section 3).

Typical results are shown in figures 12 to 14.

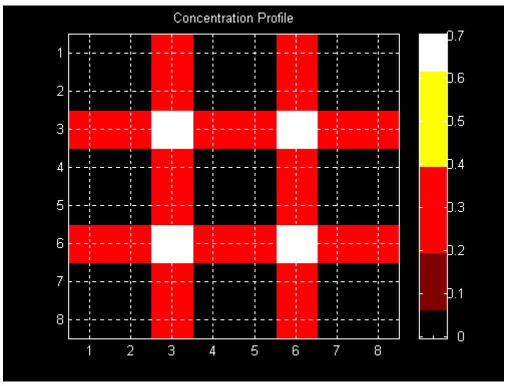

Figure 12 LBP for two orthogonal projections: two pixels flow model

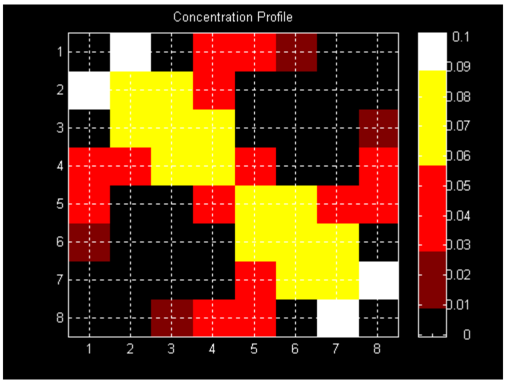

Figure 13 LBP for two rectilinear projections: two pixels flow model

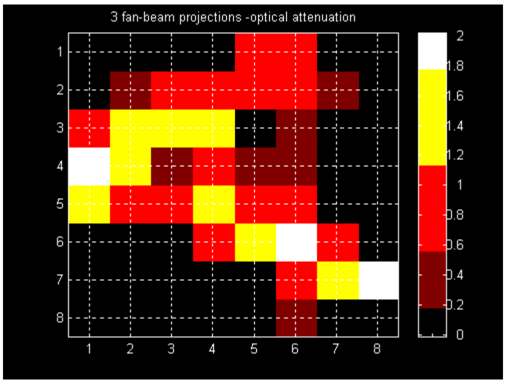

Figure 14 LBP for three fan beam projections: two pixels flow model

Results for the attenuation model are discussed in section 5.

5. DISCUSSION OF RESULTS OBTAINED WITH LBP AND FLBP

The complete set of results for the path length modelling are shown in Table 1.

Projections	Algorithm	No. of Sensors	Error %
2 Orthogonal	LBP	16	688
2 Orthogonal	FLBP	16	734
2 Rectilinear	LBP	16	962
2 Rectilinear	FLBP	16	986
2 Rect/2 Ortho	LBP	32	852
2 Rect/2 Ortho	FLBP	32	858
3 Orthogonal	LBP	24	802
3 Orthogonal	FLBP	24	860
3 fan-beam	LBP	36	412
3 fan-beam	FLBP	36	559
4 fan-beam	LBP	48	716
4 fan-beam	FLBP	48	731

Table 1. Estimated reconstruction errors: path length model.

The error for each reconstructed model was calculated by summing all the voltages in the voltage concentration matrix and dividing the sum by the ideal voltage. Generally speaking all the errors are very large as shown in Table 1. Similar values were obtained for the attenuation model.

The authors expected more projections to provide more accurate estimates of the models. Some of the large errors obtained using the back projection and filtered back projection algorithms are due to the significant smearing effect in the image due to this type of reconstruction. However, another type of error is introduced if all the sensors do not provide the same weighting in the calculations. This was very noticeable with the fan beam systems, where pixels close to the light sources are more heavily weighted than those further away. This suggests that orthogonal and rectilinear projections should be used. The errors are still unacceptably high. This lead to the hybrid reconstruction algorithm.

6. HYBRID RECONSTRUCTION ALGORITHM

Optical sensors are hard field sensors and the so the material in the flow is assumed only to vary the intensity of the received signal.

This enables *a priori* knowledge from the optical sensors to be used in the reconstruction. For an optical sensor when no objects block the path from transmitter to receiver the sensor will produce a zero output value, neglecting the effect of noise inherent in the system.

This is taken into account in the development of a hybrid reconstruction algorithm which incorporates both *a priori* knowledge and LBP in order to improve the accuracy of the image reconstruction. This algorithm is being developed using the C programming language.

The algorithm is designed for a two, three or four projection system based on orthogonal and rectilinear projections. At present the algorithm assumes binary values from the sensors, either zero for no material or one for the presence of material. Briefly, the steps involved in the algorithm are :-

(1) Generate the usual sensitivity maps for the horizontal, vertical and diagonal sensors.
(2) Initialise all sensors to zero.
(3) Read in each sensor value.
(4) If the sensor reading = 0, then any pixels traversed by that sensor's beam are set to zero and omitted from further calculations.
(5) Perform Linear Back Projection in the normal way.

This simplified algorithm resulted in the significant improvement in the measured errors.

7. CONCLUSIONS

The algorithm described in section 6 is only suitable for hard field sensors. It is unlikely to improve image reconstruction for flow regimes with a void in the pipe centre, such as annular flow. However, optical sensors are intended for use where the conveyed component ratio is less than 10% vol./vol. In this type of conveying, the material being monitored is well dispersed and experience shows that sensor outputs are often in the noise level.

Based on the design study presented in this paper, the authors are building an optical tomography system with four projections; two orthogonal and two rectilinear.

The conditioned sensor outputs will be sampled as digital integers so that the calculations are simplified and high speed is more easily obtained.

The data will be collected and processed on line using a modification of the hybrid reconstruction algorithm out-lined in the paper.

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