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An alternative method for tracking a radioactive particle inside a fluid

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HIGHLIGHTS

- A practical but general method was developed to reconstruct successive positions of a radioactive particle using the EM algorithm.
- This method permits to find the optimum voxel containing the particle after few iterations of the algorithm.
- The proposed method can track the movement of the particle with a maximum relative error equal to 7.8%.
- We can track the particle with accuracy suitable for each application varying detectors′ number in the experimental setup.

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ABSTRACT

The proposed tracking method describes the trajectory of a radioactive particle moving in a fluid as a sequence of small cubic cells occupied by successive particle positions. In addition, the EM reconstruction algorithm was applied to get the image of the unique cell which had the greatest probability to contain the particle at a given time of a test. Next, this information was useful to calculate the coordinates and velocities of the particle at that time. The method was tested in laboratory using a gamma radiation detection system, the radioisotope ^{198}Au and a mixer. According to the results, the maximum deviation found between theoretical and experimental values of the average rotating period was less than 8% and the particle's reconstructed trajectories are representative of its real movement. Thus, a paradigm shift permitted us to begin the development of an alternative method to solve the complex problem of tracking the movement of a radioactive particle inside an opaque unit.

1. Introduction

As part of noninvasive techniques used to improve quality control of industrial units, the computer automated radioactive particle tracking technique (CARPT) has already proved to be a powerful tool for modeling industrial units and process control.

Since the first method for tracking a radioactive particle was invented in the middle of the past century by Kondukov et al. (1965), CARPT is employed to characterize industrial processes (Velzen et al., 1974; Lin et al., 1985; Chaouki et al., 1997; Dudukovic, 2002, 2007). CARPT uses a radioactive tracer in the form of a small particle whose physical properties mimics the phase is being traced to evaluate the fluid′s displacement patterns as the solids motion in a fluidized bed, recirculation patterns, segregation regions or eddies within stirred tank reactors (Dudukovic, 2005; Dudukovic et al., 2006). Stirred tank reactors have been investigated employing the radioactive particle tracking technique at the University of Washington since the last decade. Using a radioactive particle of ^{46}Sc and a detection system formed by 16 scintillation detectors (NaI:Tl), satisfactory results were obtained for the characterization of fluids in liquid–liquid systems (Ramohhan et al., 2000) and liquid–solid systems (Guha et al., 2007).

Nowadays, solutions to the inverse problem of tracking a radioactive particle based on the values of gamma radiation intensity counts can be grouped in three main methods. According to the first method, the distance between the particle position and the detector center is approximated by a polynomial that depends on the photon counts. The polynomial coefficients are determined through the calibration of the detector by placing a radioactive particle at various points within the plant, measuring the gamma radiation counts in each of these points with the detector so that the radioactive particle position can be determined by using the weighted least squares method (Lin et al., 1985). Alternatively, the second method uses a Monte Carlo simulation to describe a map of gamma radiation counts. This map is based on a phenomenological model that describes the interaction of radiation with matter and depends on

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the particle position (Moslemian et al., 1992; Larachi et al., 1994). In this case, the intensity counts are normalized by adjusting them with a calibrated detector and the corresponding particle position is determined by a search process on that map. The third method seems to be an improved version of the second one due to the fact that the map of counts now is made by an artificial neural network.

The first approach viewing to carry out a test in an industrial unit employing CARPT with four detectors was developed by Shehata (2004) to know the dynamics of spheres containing uranium in a High Temperature Gas Reactor (HTGR). This method employs three detectors to locate the particle in the *XY* plane and another detector to locate the same particle along the *Z* axis. The four detectors are mounted on a motorized platform capable of performing vertical movement along the reactor. In the test performed, the counts in the photo peak related to the gamma radiation emitted by the particle were doubled because it was formed by the radioisotope ^{60}Co, which has two well defined energy photo peaks (662 keV and 1400 keV). This equates to perform a test employing the second method (Larachi et al., 1994) with a monoenergetic source of gamma radiation and a detection system with eight detectors.

In summary, all methods to implement CARPT are intended to a high accuracy measurement of the radioactive particle instantaneous position without considering that some applications do not need it.

The aim of this study was to develop a practical but general CARPT method (Vieira, 2009). The key idea to locate the particle is to include a position factor in an adequate image reconstruction algorithm and run it until the most probable particle position be found. This new factor is the probability of a radioactive particle to be inside some volume element of the unit so that its numerical value is related to the intensity counts.

2. Methodology

The main task is to obtain a set of punctual images of the activity of a radioactive source moving in the unit during a determined period of time to estimate their instantaneous positions $X(t)$, $Y(t)$ and $Z(t)$. After measuring a set of intensity counts with a determined frequency, the punctual images are reconstructed as a function of time, using the EM algorithm, a maximum likelihood image reconstruction method.

2.1. The physical model

As with all algebraic reconstruction algorithms, decomposition of the space involving the object of interest into a grid of small cells or voxels is needed to obtain its image. Generally, in a 3D domain, these voxels are cubic cells whose geometry fits well in a cartesian coordinate system. That is, this method is independent of the object geometry, either the human body or a cylindrical industrial unit, as illustrated in Fig. 1.

The main parameters for a correct particle tracking can be associated to each voxel as a function of its relative position to each detector, which characterizes the vector *W*, also called the Point Spread Function (PSF) of the system.

To find the vector F containing the radioactive distribution inside the unit, it is necessary to solve the system represented by Eq. (1). It is a list of m equations with identical unknown variables, that is, the i_{th} equation contains l^3 unknown variables f_j and the same number of w_{ij} coefficients.

$$C = WF + \varepsilon \tag{1}$$

In the present case, *m* is much fewer than l^3; consequently, the number of solutions is infinite. Then, it was necessary to employ a statistical method to find the best solution, and those proposed by Legoupil et al. (1996) to reconstruct a radioactive distribution inside an opaque vessel was chosen. In this case, if Δt is small enough so that particle′s position does not change between *t* and $t+\Delta t$, the coefficients w_{ij} and the counts c_i are positive constants and the uncertainty ε can be negligible using the best experimental conditions. Under these assumptions, Eq. (1) is a linear system.

According to Fig. 1, detectors′ coordinates are relative to the center of the lower base of the cylindrical unit and they may vary according to the dimensions of the unit.

2.2. Description of the EM reconstruction algorithm

The expectation maximization (EM) method is one of the iterative methods employed in image reconstruction applications (Lange and Carlson, 1984). It computes the maximum likelihood of a quantity of interest; for example, in the case of emission tomography, the quantity to be maximized is the probability that experimental data yield the reconstructed image.

Table 1 describes the notation referred to the EM algorithm applied to the motion of a radioactive particle. The linear dimension of the j_{th} voxel is greater than or equal to the diameter of the radioactive particle, and the value *l* depends on the number of voxels needed to involve the industrial unit in a real scale, as the grid involving the cyllinder in Fig. 1. Considering that photons emitted by the source can be scattered or absorbed by the medium between the source, located in the $\mathrm{j_{th}}$ position, and the i_{th} detector, some factors have to be estimated, in accordance with the basic principles of radiation detection measurements (Knoll, 1999; Tsoulfanidis, 1995). The factors are the attenuation factor, T_{ij}, the build-up factor, B_{ij}, and the solid angle, Ω_{ij} (Oblozinsky and Ribanski, 1971). Excepting *A*, *M* and *m*, that are constant values, the other quantities listed in Table 1 are estimated for the minimum time interval Δt needed to measure a set of *m* counts synchronously.

A position factor was included in the EM algorithm as a first approximation to check the hypothesis that this algorithm would be able to find the optimum voxel after a few number of iterations.

2.3. Determination of the position-factor

Position-factor of each j_{th} voxel represents the probability of the radioactive particle is passing through the center of that voxel exactly in the instant t of the tracking. In order to evaluate this factor, lets calculate the standard deviation of errors between the experimental (*A*) and calculated values of the particle's activity, the quantity E_j expressed in Eq. (2). Next, the ratio between the smallest standard deviation found throughout the matrix *M* ($E_{jmín}$) and each value of E_j gives the factors FX_j, as in Eq. (2).

$$E_{ij} = A - \frac{c_i}{(\Omega_{ij}\times T_{ij}\times B_{ij}\times \Gamma \times \Delta t)}$$

$$E_j = \left(\left(\frac{1}{m}\right)\times\left(\textstyle\sum_{i=1}^{m} E_{ij}^2\right)\right)^{1/2}$$

$$\mathrm{FX}_j = \frac{{E_{j\,min}}^2}{E_j} \tag{2}$$

2.3.1. Application of the EM algorithm

2.3.1.1. The Estimation-step. Lets consider the product $\nu_j \times p_{ij}$ as the expected number of photons emmited by the j_{th} voxel′s activity that are registered by the i_{th} detector, the product $\sum_{j=1}^{l^3} \nu_j \times p_{ij}$ as the expected number of photons from l^3 voxels that are registered by the $\mathrm{i_{th}}$ detector and the complete data set γ_i, expressed by Eq. (3), as the sample space formed by the sum of the probability density functions of the number of photons emitted by all voxels