

Proceeding Paper

Spatial and Time-Series 4D Infrared Gas Cloud Imaging Reconstructed from Infrared Images Measured in Multiple Optical Paths [†]

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Abstract: Current gas leak detection systems rely on the human senses and experience. It is necessary to develop remote and wide-range gas leak monitoring systems that enable us to quantitatively estimate the gas concentration distribution and amount of leaked gas. In this research, an infrared camera was used to detect gas leakage. We developed a 4D, i.e., 3D spatial plus time-series, gas cloud imaging system, in which time-series 2D gas image data obtained in multiple optical paths were computed to reconstruct 4D gas cloud data. The 4D imaging of gas clouds was successfully accomplished in a very short computation time by applying the Elastic Net based on L1 and L2 regularization to the Fourier components of the time-series infrared gas images.

Keywords: infrared measurement; leaked gas cloud; the Fourier analysis; computed tomography; regularization regression



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1. Introduction

It is important to detect gas leakage in aged plant facilities to prevent fire and explosion accidents. Currently, detection of gas leakage and estimation of the diffusion status relies on the human senses and experience, using information from gas detectors installed at fixed points. Since skilled workers are expected to retire in the near future, it is necessary to develop remote and wide-range gas leak monitoring systems. Leaked gas can be detected through the absorption of infrared radiation by the gas and the infrared radiation emitted from the gas itself. A 4D, i.e., 3D spatial plus time-series, gas cloud imaging system helps estimate the gas concentration distribution and amount of leaked gas. This research group has succeeded in performing 4D imaging by reconstructing 3D gas images obtained with multiple infrared cameras using the ART method as an inverse tomographic analysis method, reconstructing the gas shape by using projection data in four directions, and tracking the time-sliced changes in the gas shape [1]. However, this time slicing 4D reconstruction method requires extensive computation time to reconstruct each frame, and artifacts were observed due to computation errors. We propose a frequency slicing method taking advantage of the fact that the gas cloud existence region is limited, so-called sparsity exists, and the gas cloud has frequency characteristics. The Fourier component of the time-series infrared image is reconstructed in 3D to speed up the computation and reduce noise. In this new inverse tomographic technique, the Elastic Net, which incorporates the L1 norm effective for sparsity problems, is introduced. By combining these techniques, the effectiveness of 4D imaging from a small number of directions is investigated using simulation data.

2. 4D Imaging Method Combining 3D Reconstruction and Fourier Analysis

2.1. Elastic Net Reconstruction Method

In gas plants, it is difficult to acquire data in many directions like in X-ray CT. Therefore, the sparsity of gas clouds is incorporated in the identification of 3D gas distribution. The Elastic Net, which incorporates the L1 norm effective for sparse regularization, is applied [2]. The Elastic Net finds estimates by minimizing the regularized sum-of-squares error function $R_\lambda(\vec{x})$ expressed as follows:

$$R_\lambda(\vec{x}) = \frac{1}{M}(\vec{y} - A\vec{x})^T(\vec{y} - A\vec{x}) + \lambda \sum_{j=1}^N \left(\alpha \|x_j\|_1 + \frac{1-\alpha}{2} \|x_j\|_2^2 \right) \quad (1)$$

Let $\vec{x} = (x_1, \dots, x_N)^T$ be the cross-sectional image to be estimated and $\vec{y} = (y_1, \dots, y_M)^T$ be the projection data obtained through measurement, where M is the total number of measured projection data and N is the number of pixels in the cross-sectional image. The projection operation that relates $\vec{x}$ and $\vec{y}$ is represented by an $M \times N$ coefficient matrix $A = \{a_{ij}\}$. The calculation is iterated until the difference between the pre- and post-update values of $R_\lambda(\vec{x})$ is sufficiently small or the number of iterations reaches a certain value, where λ is a positive regularization parameter that adjusts for sparsity and α is a parameter that adjusts the ratio between the L1 and L2 penalty terms and takes values between 0 and 1. This method is equivalent to the least squares method for $\lambda = 0$, the regression method for $\alpha = 0$, and the Lasso regression method for $\alpha = 1$. Although the Lasso regression can simultaneously select variables and calculate estimates, the number of variables that can be selected is at most M in the $N > M$ case. It is considered difficult to accurately reconstruct a wide range of gases for this study due to insufficient data, i.e., the small value of M . Therefore, the Elastic Net, a method that combines the Ridge and the Lasso regressions, was used to overcome the limitations of the Lasso regression.

2.2. 4D Imaging Method Using Fourier Analysis

Considering that gas clouds have distribution characteristics dependent on frequency, the Fourier series expansion was newly applied to reduce calculation errors and the number of image reconstructions, as well as to reduce the influence of noise. The Fourier series expansion was applied to the image data of a gas jet captured using a camera, and the image data can be decomposed into frequency-specific images. The following is a description of the Fourier analysis method.

When time series data for T seconds are obtained, the pixel value $P(t)$ at any position of the image data at time t is expressed by the following equation using the Fourier series expansion.

$$P(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left(a_n \cos \frac{2\pi n}{T} t + b_n \sin \frac{2\pi n}{T} t \right) \quad (2)$$

where a_n and b_n are the Fourier coefficients of the degree n , and are expressed as.

$$a_n = \frac{2}{T} \int_0^T P(t) \cdot \cos \frac{2\pi n}{T} t dt \quad (3)$$

$$b_n = \frac{2}{T} \int_0^T P(t) \cdot \sin \frac{2\pi n}{T} t dt \quad (4)$$

Equation (2) shows that the pixel value $P(t)$ can be expressed as a series of sine and cosine frequency components, with a_n and b_n being the amplitudes.

In the 4D imaging in this study, the Fourier series expansion is used for the video data to create images showing the distribution of amplitudes a_n and b_n for each frequency component. Then, the 3D distribution of each frequency component is reconstructed by the Elastic Net. The 3D image of each frame is created by substituting the 3D distribution for

each frequency component into a_n and b_n expressed by Equation (2) and substituting the time for t . By connecting these images in a time series, a 4D image is reconstructed.

3. Reconstruction Simulation

3.1. Numerical Simulation of Leakage Gas Flow

Figure 1 shows a schematic of a 3D simulation of a gas jet. The simulation condition is that methane gas is jetting upward from the center of the 3D space. The gas flow rate is 10 L/min, the wind direction is parallel to the z-axis, and the wind speed is 1 m/s. Here, 4D imaging is performed in this 3D space using data captured with cameras from four directions. The distance between the gas leak source and the camera is 30 m. The camera is positioned on the z-axis extension from the gas leak source, and the angle is 0° . First, 2D images are obtained by projecting the simulated 3D image in four directions at 45° increments. Figure 2a–d show 8-bit images from 0° , 45° , 90° , and 135° , respectively, obtained from the simulation. The 2D video is 30 frames/s, with a size of 100×100 pixels. The pixel size of the infrared image is 40 mm/pixel.

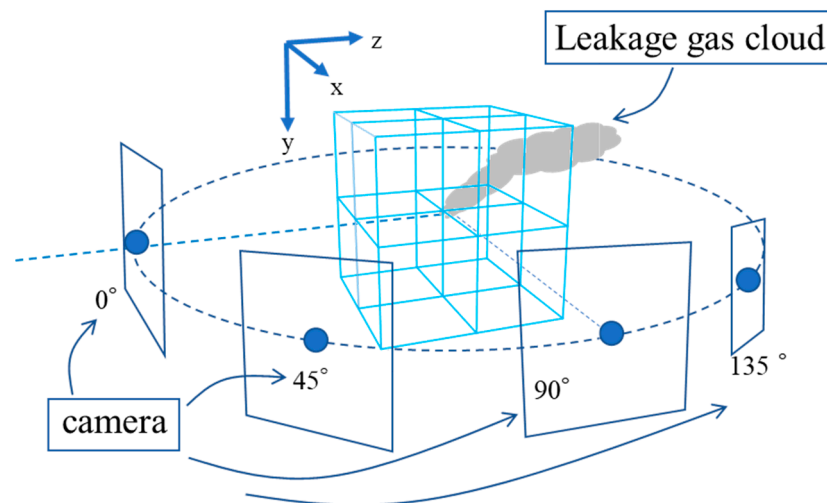


Figure 1. The density distribution volume data mesh and the projected images for each viewpoint.

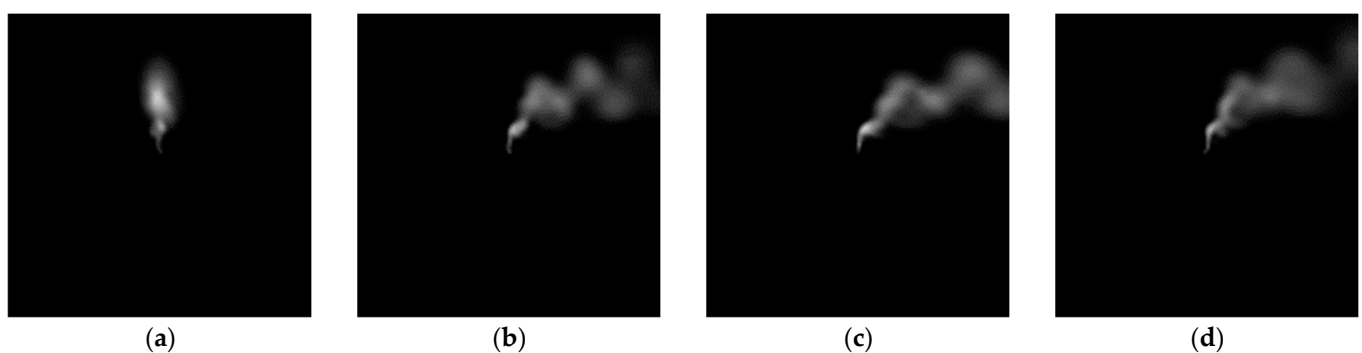


Figure 2. Simulation images (a) captured from a direction at $\theta = 0^\circ$, (b) captured from a direction at $\theta = 45^\circ$, (c) captured from a direction at $\theta = 90^\circ$, and (d) captured from a direction at $\theta = 135^\circ$.

3.2. 4D Reconstruction

Based on the simulation images in four directions, the 4D imaging results are shown in Figure 3 under the following conditions: $n = 0 \sim 5$ for the order of the Fourier series expansion used for image reconstruction, and $\alpha = 0.1$ for the Elastic Net. The termination condition is that the difference of the updated values is less than or equal to 10^{-2} or the number of iterations is 10^5 times. The solution was calculated using the glmnet library in the R language, and the regularization parameter λ was calculated for each cross-section using

the `cv.glmnet` function in the same library [3]. It is seen from Figure 3 that artifacts caused by calculation errors are reduced due to the L1 norm sparsification, and the region where gas is present is appropriately reconstructed. It is also clear that the shape and movement of the gas can be captured even when the frequency components used in the reconstruction are limited. By limiting the components, the computation time for reconstruction was drastically reduced. Although omitted due to page number limitation, 4D reconstruction was possible from images projected from two and three directions.

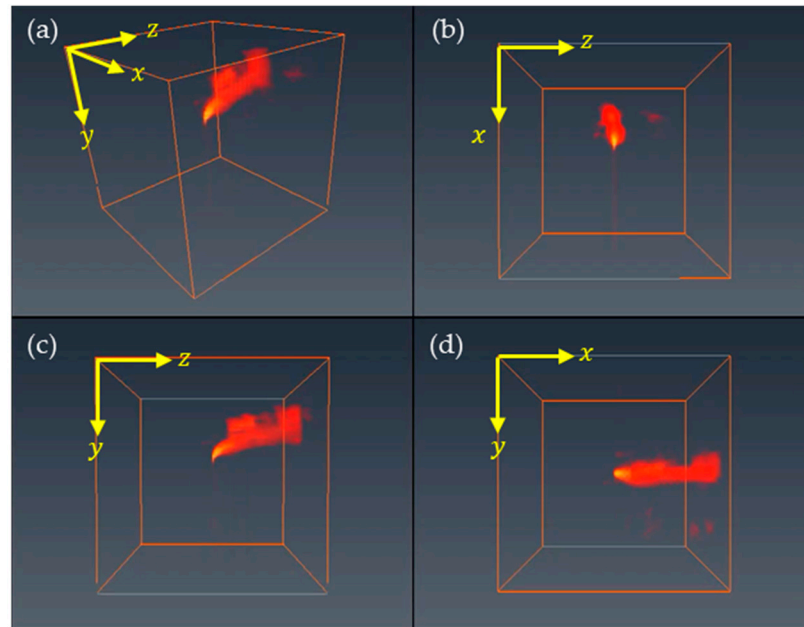


Figure 3. Estimated 4D image of leakage gas cloud: (a) plane view, (b) view from the zx-plane, (c) view from the yz-plane, (d) view from the xy-plane.

4. Conclusions

In order to prevent explosions and fires caused by leaking gas, it is necessary to develop remote and wide-range gas leak monitoring systems. We proposed a frequency slicing 4D reconstruction method that represents a 3D spatial plus time-series gas cloud through inverse tomography analysis of infrared data from multiple optical paths. By combining the Fourier analysis and the Elastic Net, we succeeded in implementing 4D imaging of leaking gas from infrared images taken from four directions. Artifacts are reduced and the computation time is significantly reduced.

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