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3D Density Field Reconstruction of Vehicles Exhaust Plumes using Background Oriented Schlieren Tomography based on Windowed Fourier Transform and Graphical Phase Analysis

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Summary:
This work presents a 3D Gas Schlieren Imaging Sensor (GSIS) system. The 3D-GSIS system allows to construct 3-D density fields of gas flows and vehicle exhaust plumes from conventional camera images, by using an innovative Windowed Fourier Transform-based Graphical Phase Analysis (WFT-GPA) algorithm and state-of-the-art Optical Flow techniques to calculate and construct density fields. The system will be combined with advanced remote emission sensing (RES) systems to measure the direct concentration of pollutants in the vehicle exhaust plumes.

Keywords: background oriented schlieren imaging, BOS tomography, 3D density fields, remote emission sensing, exhaust plume imaging

Background, Motivation and Objective

Air pollution is a significant public health issue, with on-road traffic emissions playing a pivotal role, especially in urban areas. Remote emission sensing (RES) is an advanced method for monitoring emissions from thousands of vehicles in real-world conditions. Advanced RES systems use absorption spectroscopic techniques to determine the concentration ratios of pollutants relative to CO_2, as this allows conclusions about the emissions related to fuel consumption.

To accurately measure the concentrations of pollutants in vehicle exhaust plumes, it is necessary to calculate the absorption path length, which refers to the extent of the exhaust plume in the direction of the laser beam from the RES system. Hence, if we can measure the size and extent of the exhaust plume in the direction of the laser beam of the RES system, we can measure the absolute concentration of pollutants according to Beer-Lambert Law [1]. The 2D Gas Schlieren Imaging Sensor (GSIS) System has been developed for qualitative and quantitative analysis of vehicle exhaust plumes [2]. It supports a vertical RES system, which means a laser transmitter is placed above the road and transmits a laser beam from the top toward the road. 2D images of exhaust plumes from single side only give enough information to calculate the laser beam's absorption path length in fixed setups.

This work presents a 3D-GSIS system that can construct the 3D density fields of vehicle exhaust plumes and other turbulent flows using background-oriented Schlieren (BOS) tomography. The 3D-GSIS system uses an advanced and efficient Windowed Fourier Transform-based Graphical Phase Analysis (WFT-GPA) and state-of-the-art Optical Flow (OF) techniques to calculate displacement fields and construct density fields. With the 3-D density fields of exhaust plumes, we can efficiently find the absorption path length of the laser beam from any direction.

Description of the System

The 3D-GSIS system is made of 8 cameras covering the angle of 160° from 0° to 160° as shown in Fig. 1.

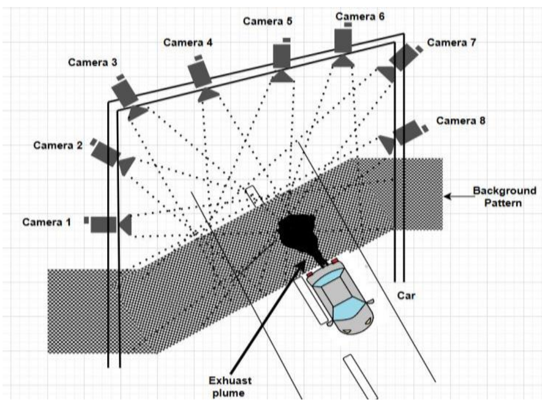

Fig. 1. Road Setup of 3D-GSIS System

The number of cameras can be adapted on the working conditions and applications, to adapt coverage and resolution. A pattern is placed in front of each camera unit. The gas flow and vehicle exhaust plume are located in the middle so that the plume is in the field of view of each camera. Each camera captures the image of the pattern board with and without the flow. The image pair is then used to calculate the displacement field using WFT-GPA and OF. The 2D line of sight integrated density fields are calculated using the displacement fields and solving the Poisson equation [3]. 3D density field is constructed using the tomographic reconstruction based on the Simultaneous Algebraic Reconstruction Technique (SART). The workflow of the 3D-GSIS system is shown in Fig. 2.

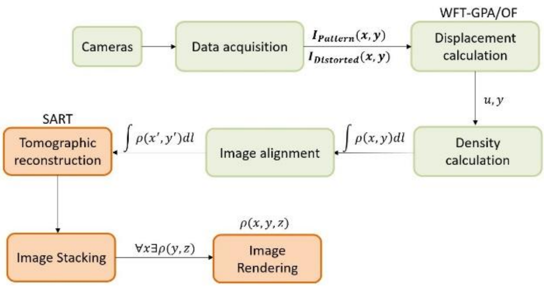

Fig. 2. Workflow of 3D-GSIS System

Results

The 3D-GSIS system was set up in the lab and tested with gas flows. Initially, the system experimented with the gas flow containing 10% air and 90% CO_2. The constructed 2D line-of-sight integrated density field and 3D density field are shown in Fig. 3 and Fig. 4.

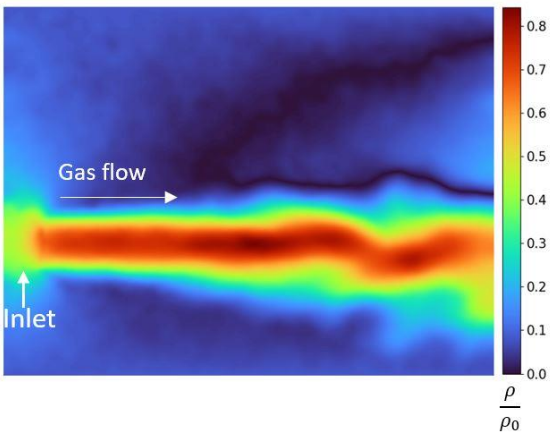

Fig. 3. 2D Density Field of Gas Flow

The 3D-GSIS system was also set up the Inffeldgasse campus of Graz University. It is being tested with passing cars. Fig. 5 and Fig. 6 show the constructed 2D and 3D density field of a car's exhaust plume.

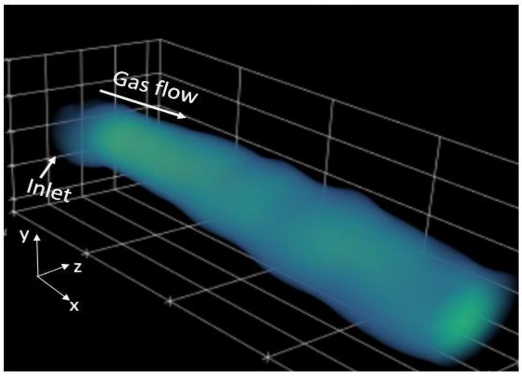

Fig. 4. 3D Density Field of Gas Flow

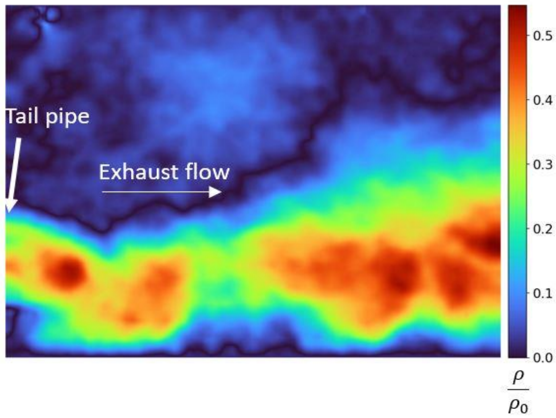

Fig. 5. 2D Density Field of Vehicle Exhaust Plume

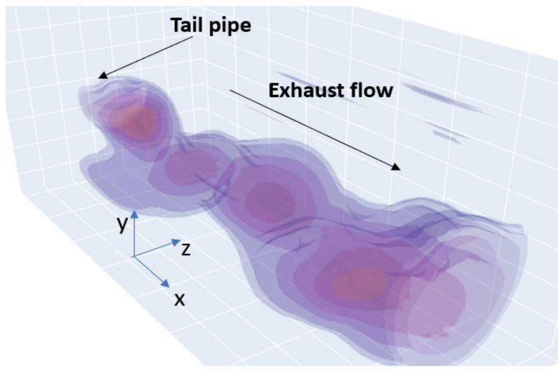

Fig. 6. 3D Density Field of Vehicle Exhaust Plume

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