ONERA
THE FRENCH AEROSPACE LAB

PROPOSITION DE SUJET DE THÈSE

Intitulé : Neural representations for reconstruction of turbulent flows with background-oriented shlieren imaging

Référence : **TIS-DTIS-2025-37**
(à rappeler dans toute correspondance)

Début de la thèse : 01/10/2025	**Date limite de candidature :** 01/05/2025

Mots clés : inverse problems, neural networks, tomography, schlieren photography, physics informed neural networks (PINNs)

Profil et compétences recherchées

Master 2 ou école d'ingénieur avec filière recherche dans au moins l'un des domaines suivants : vision par ordinateur / mécanique des fluides / signal et image. Intérêt souhaité pour tous ces domaines

Présentation du projet doctoral, contexte et objectif

Background-oriented Schlieren (BOS) is a simple non-intrusive measurement technique exploiting images distorted by turbulence or mirage-like effects. Since its origin, it has evolved from a qualitative visualization technique, to industrial applications for gas leak detection [1] and advanced quantitative metrology of high-speed gas flows, shedding light into fundamental turbulence phenomena in fluid dynamics [2]. The simplicity of BOS experimental setup is balanced by a high demand on non-trivial processing in order to extract density fields and associated physical quantities, BOS measurements providing line integrals along optical ray paths. It thus shares many features with computed tomography (CT), and more precisely with sparse-view CT (SVCT) [3] due to fundamental technological limits in BOS.

A major problem when applying SVCT to the study of turbulent flow phenomena lies in the difficulty of constituting experimental training databases, as performed for instance in medical CT [4]. In other terms, supervised training of neural networks (NN) for volumetric reconstruction of physical parameters can only rely on numerical simulations that are costly, raising the question of calibration to experimental data. A non-supervised attractive alternative is the consideration of Physics Informed Neural Networks (PINNs) that encode the searched physical quantity in a Multi-Layer Perceptron (MLP) which is fitted to measurements and physical conservation equations [5][6]. Such methods have already been applied to BOS measurements in specific settings, namely the case of extraction of steady features of axisymmetric jets [6], and extraction of time-resolved low dynamic 3D flows [7].

As impressive such achievements can be, reconstruction of time resolved high-dynamic flow remains presently and unsolved issue. The goal of the thesis is to bridge the gap between present status and this challenging objective.

Different tracks can be followed to bridge this gap. In the case of PINNs, one may question the traditional tuning of the expressivity of MLP through Fourier features [8] and its ability to encode highly turbulent flows. Moreover, what is the interplay of these specifications with regression losses used to infer their parameters? In particular, the work of [7] considers that time and space inputs in the MLP have equivalent roles, while distinction between the two categories of inputs appear only in the regression losses. Can such distinction be considered beforehand within the NN architecture? An approach related to this topic is suggested in [9] where the same NN is applied along time while its weights are trained using a physical spatio-temporal loss on spatio-temporal batches. Although somehow overly simplistic, such time-independent architectures have been shown to provide instantaneous quantities that are not directly observable [10]. Such an approach would certainly provide an intermediate 3D step toward a full 3D+time reconstruction.

The different tested processing concepts will be developed and evaluated within the DTIS in Palaiseau and tested on a synthetic dynamic 3D flow generated by the DMPE in Toulouse. As a final step, an experimental dataset will be generated by the DMPE in its facilities in order to validate the processing algorithms.

[1] Boudreaux *et al.* Application of reference-free natural background–oriented schlieren photography for visualizing leakage sites in building walls. *Building and Environment*, 2022 doi.org/10.1016/j.buildenv.2022.109529.

[2] Nicolas *et al.* A direct approach for instantaneous 3D density field reconstruction from background-oriented schlieren (BOS) measurements. *Experiments in fluids*, 2016, vol.

[3] Guan *et al*, “Generative modeling in sinogram domain for sparse-view ct reconstruction,” IEEE Transactions on Radiation and Plasma Medical Sciences, 2023.

[4] C. McCollough *et al*, “Overview of the low dose CT grand challenge,” Medical physics, 2016

[5] Raissi *et al*. Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations. *Journal of Computational physics*, 2019.

[6] Molnar, *et al*, Estimating density Velocity and Pressure fields in supersonic flows using Physics Informed BOS, arxiv:2208/04280v1

[7] Cai *et al.* Flow over an espresso cup: inferring 3-D velocity and pressure fields from tomographic background oriented Schlieren via physics-informed neural networks. *Journal of Fluid Mechanics*, 2021

[8] Tancik et al, M. Fourier Features Let Networks Learn High Frequency Functions in Low Dimensional Domains, NeurIPS 2020.

[9] Kelshaw et al, Super-resolving sparse observations in partial differential equations: A physics-constrained convolutional neural network approach. arxiv.org/abs/2306.10990

[10] Mons *et al*, Dense velocity, pressure and Eulerian acceleration fields from single-instant scattered velocities through Navier--Stokes-based data assimilation, *Measurement Science and Technology*, 2022

Collaborations envisagées

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