# Note on Open Source Matlab Programs for Global Flow Diagnostics

Tianshu Liu
Department of Mechanical and Aerospace Engineering
Western Michigan University, Kalamazoo, MI 49008, USA

The open source Matlab programs are developed for the following global flow diagnostic techniques.

(1) OpenOpticalFlow_v1: Optical flow method for global velocity diagnostics based on various flow visualizations;

(2) OpenOpticalFlow_PIV_v1: Hybrid optical-flow-cross-correlation method for high-resolution PIV;

(3) OpenSkinFrictionFromGLOF_v1: Skin friction diagnostics based on global luminescent oil film (GLOF) visualization;

(4) OpenSkinFrictionFromTemperature_v1: Skin friction diagnostics based on surface temperature visualization;

(5) OpenSkinFrictionFromScalar_v1: Skin friction diagnostics based on surface scalar visualization;

(6) OpenSkinFrictionFromPressure_v1: Skin friction diagnostics based on surface pressure visualization;

(7) OpenHeatFluxFromTSP_v1: Heat flux measurements based on temperature-sensitive coatings;

(8) OpenPhotogrammetry_v1: Photogrammetry applied to aerodynamics and flui mechanics.

(9) OpenPressureFromVelocity_v1: Determining pressure from velocity,

(10) OpenSurfacePressureFromSkinFriction_v1: Determining surface pressure from skin friction.

(11) Open_PSP_TSP_v1: Some processing tools for PSP/TSP measurements.

## 1. OpenOpticalFlow

OpenOpticalFlow is an open source optical flow program in Matlab for extraction of high-resolution velocity fields from various flow visualization images. This program is a useful tool for researchers to use the optical flow method in various flow measurements. The principles of the optical flow method are concisely described in references (e.g. Liu 2017), including the physics-based optical flow equation, the variational solution, and errors. The central parts include the main program, relevant subroutines and selection of the relevant parameters in optical flow computation. Examples are given to demonstrate the applications of the optical flow method.

**References:**

Liu, T., Shen, L. 2008 Fluid flow and optical flow J Fluid Mech 614, 253-291.

Liu, T., Wang, B., Choi, D. 2012 Flow structures of Jupiter's Great Red Spot extracted by using optical flow method Phy Fluids 24, 096601-13.

Liu, T., Nink, J., Merati, P., Tian, T., Li, Y., Shieh, T. 2010 Deposition of micron liquid droplets on wall in impinging turbulent air jet Exp Fluids 48, 1037-1057.

Hayasaka, K., Tagawa, Y., Liu, T, Kameda, M. 2016 Optical-flow-based background-oriented schlieren technique for measuring a laser-induced underwater shock wave Exp Fluids, 57, 179.

Liu, T., Merat, A., Makhmalbaf, MHM., Fajardo, C, Merati P, 2915 Comparison between optical flow and cross-correlation methods for extraction of velocity fields from particle images Exp Fluids, 56, 166-189.
Wang B, Cai Z, Shen L, Liu T 2015 An analysis of physics-based optical flow method J Comp Appl Math 276, 62-80.
Liu T, Sanyanagi KM, Brueshaber S, Ingersoll AP, Dyudina UA, Ewald SP 2019 Saturn's north polar vortex structure extracted from cloud images by the optical flow method, Journal of Geophysical Research: Planets, Vol. 124, Issue11, pp. 3041-3062.
Liu T 2017 OpenOpticalFlow: An open source program for extraction of velocity fields from flow visualization images, Journal of Open Research Software, 5:29.

## 2. OpenOpticalFlow_PIV

OpenOpticalFlow_PIV is a hybrid method for particle image velocimetry (PIV) to overcome the limitations of the optical flow method applied to PIV images with large displacements. The main elements of the hybrid method include a cross-correlation scheme for initial estimation, a shifting scheme for generating a shifted image and an optical flow scheme for obtaining a refined high-resolution velocity field. In addition, a pre-processing scheme is used for correcting the illumination intensity change. As described in reference, the accuracy of the hybrid method is evaluated through simulations in a parametric space in comparisons with the typical correlation methods and optical flow method. Further quantitative comparisons are made in PIV measurements in a circular air jet.

**References:**

Liu T, Salazar D, Fagehi H, Ghazwani H, Montefort J, Merati P, 2019 Hybrid Optical-flow-cross-correlation method for particle image velocimetry, Journal of Fluids Engineering, appear online.

## 3. OpenSkinFrictionFromGLOF

OpenSkinFrictionFromGLOF is a method for extracting a skin friction fields from a sequence of global luminescent oil-film (GLOF) images obtained on a surface in aerodynamic testing. Luminescent oil is used since the oil-film thickness is proportional to the luminescent emission intensity when the oil is optically thin. In experiment, a thin luminescent oil film is brushed or sprayed on a surface in a region of interest before starting a wind tunnel, and it is illuminated by light sources with a suitable wavelength such as ultraviolet (UV) lights. Therefore, oil-film thickness measurement is converted to luminescent intensity measurement by using a camera with a suitable optical filter. After flow is turned on, a time sequence of evolving GLOF images is acquired. The thin-oil-film equation is re-cast to an optical flow equation, and a variational method is used for solving this optical flow problem for skin friction.

**References:**

Liu T, Woodiga S, Ma T, 2011 Skin friction topology in a region enclosed by penetrable boundary Exp Fluids; 51: 1549-1562.
Liu T, Montefort J, Woodiga S, Merati P, Shen L. 2008 Global luminescent oil film skin friction meter. AIAA J., 46(2): 476-485.
Woodiga S, Liu T. 2009 Skin friction fields on delta wings. Exp Fluids, 47: 897-911.

Woodiga S, Salasar DM, Wewengkang P, Montefort J, Liu T. 2018 Skin-friction topology on tail plate for tractor-trailer truck drag reduction. J. of Visualization, 21: 1017-1029.
Woodiga S, Liu T, Ramasamy RSV, Kode S. 2015 Effects of pitch, yaw, and roll on delta wing skin friction topology. Journal of Aerospace Engineering;
Husen N, Liu T, Sullivan JP. 2018 The luminescent oil film flow tagging (LOFFT) skin friction meter applied to FAITH hill. AIAA J., 56(10): 3875-3886.
Husen N, 2017 Skin friction measurements using luminescent oil films, Ph.D. Thesis, Purdue University.
Husen N, Liu T, Sullivan JP. 2018 The ratioed image film thickness meter. Measurement Science and Technology, 29(6), 065301.
Zhong H, Woodiga S, Wang P, JShang J, Cui X, Wang J, Liu T. 2015 Skin friction topology of wing-body junction flows," European Journal of Mechanics – B/Fluids, 53: 55-67.
Lee T, Nonomura T, Asai T, Liu T. 2018 Linear-least-squares method for global luminescent oil-film skin-friction field analysis. Review of Scientific Instruments, 89(6): 065106.
Tran TH, Amboa T, Lee T, Chen L, Nonomura T, Asai K. 2018 Effect of boattail angles on the flow pattern on an axisymmetric afterbody surface at low speed, Experimental Thermal and Fluid Science, 99; 324-335.
Tran TH, Ambo T, Lee T, Ozawa Y, Chen L, Nonomura T, Asai K. 2019 Effect of Reynolds number on flow behavior and pressure drag of axisymmetric conical boattails at low speeds, Experiments in Fluids, 60(3), 36.

4. **OpenSkinFrictionFromTemperature**

OpenSkinFrictionFromTemperature is a program for extracting a skin friction fields based on a relation between skin friction and surface temperature derived from the energy equation of flow. A variational method is used to solve this inverse problem for skin friction when the source term is modeled.

**References:**

Liu T, Woodiga S. 2011 Feasibility of global skin friction diagnostics using temperature sensitive paint. Meas. Sci. Technol. 22: 115402.
Miozzi M, Capone A, Di Felice A, Klein C, Liu T. 2016 Global and local skin friction diagnostics from TSP surface patterns on an underwater cylinder in cross flow. Physics of Fluids, 28(12): 12410.
Liu T 2013 Extraction of skin-friction fields from surface flow visualizations as an inverse problem. Meas. Sci. Technol., 24: 124004.
Liu T 2019 Global skin friction measurements and interpretation," Progress in Aerospace Sciences, appear online.

5. **OpenSkinFrictionFromScalar**

OpenSkinFrictionFromScalar is a program for extracting a skin friction fields based on a relation between skin friction and surface scalar concentration derived from the mass transfer equation of flow. A variational method is used to solve this inverse problem for skin friction when the source term is modeled.

**References:**

Liu T, Woodiga S, Gregory J, Sullivan JP. 2014 Global skin friction diagnostics based on surface mass-transfer visualizations. AIAA J., 52(11): 2369-2383.
Liu T, Makhmalbaf MHM, Ramasamy RSV, Kode S, Merati P. 2015 Skin friction fields and surface dye patterns on delta wings in water flows. J. of Fluids Engineering, 137: 071202-1-14.
Liu T, 2013 Extraction of skin-friction fields from surface flow visualizations as an inverse problem. Meas. Sci. Technol., 24: 124004.
Liu T, 2019 Global skin friction measurements and interpretation, Progress in Aerospace Sciences, appear online.

6. **OpenSkinFrictionFromPressure_**

OpenSkinFrictionFromPressure_ is a program for extracting a skin friction fields based on a relation between skin friction and surface pressure derived from the NS equations. A variational method is used to solve this inverse problem for skin friction when the source term is modeled.

**References:**

Liu T, Misaka T, Asai K, Obayashi S, Wu JZ. 2016 Feasibility of skin-friction diagnostics based on surface pressure gradient field. Meas. Sci. Technol., 27(12): 125304.
Liu T 2018 Skin-friction and surface-pressure structures in near-wall flows. AIAA J., 56(10): 3887-3896.

7. **OpenHeatFluxFromTSP_**

OpenHeatFluxFromTSP contains the programs to calculate heat flux fields from time history of the surface temperature measured using TSP by solving the inverse heat transfer problem for the two-layer structure. The exact analytical inverse heat transfer solution of the one-dimensional heat conduction equation for a polymer layer (TSP) on a semi-infinite base and a finite base was obtained under the assumption that the thermal properties are constants. The analytical inverse heat transfer method has been used to calculate the heat flux fields in temperature-sensitive-paint measurements. The numerical inverse heat transfer method (referred to as the numerical method hereafter) has been developed for the two-layer structures with the temperature-dependent thermal properties of the materials. This Matlab toolbox contains the programs and functions developed in references.

**References:**

Liu, T, Cai, Z, Lai, J, Rubal, J, Sullivan, JP. 2010 Analytical method for determining heat flux from temperature-sensitive-paint measurements in hypersonic tunnels. Journal of Thermophysics and Heat Transfer, 24(1): 85-94.
Cai, Z, Liu, T, Wang, B, Rubal, J, Sullivan, JP.2011 Numerical inverse heat transfer analysis for temperature-sensitive-paint measurements in hypersonic tunnels. Journal of Thermophysics and Heat Transfer, 25(1): 59-67.
Liu, T, Wang, B, Rubal, J, Sullivan, JP. 2011 Correcting lateral heat conduction effect in image-based heat flux measurements as an inverse problem. International Journal of Heat and Mass Transfer, 54: 1244-1258.
Liu, T, Rubal, J, Ward, C, Sullivan, JP, Schneider, S. 2013 Heat-flux measurements with temperature sensitive paint in a Mach-6 quiet tunnel. Journal of Spacecraft and Rockets, 50(2): 282-293.

Liu, T, Montefort, J, Stanfield, S, Palluconi, S, Crafton, J, Cai, Z. 2018 Analytical inverse heat transfer method for temperature-sensitive-coating measurement on a finite base. International Journal of Heat and Mass Transfer, 118: 651-662.

Cai, Z, Liu T, Montefort, J. 2018 Numerical inverse method for calculating heat flux in temperature-sensitive-coating measurement on a finite base, Journal of Heat and Mass Transfer, 127:1099-1113.

Liu T, Montefort J, Stanfield S, Palluconi S, Crafton J. 2019 Correction for effect of temperature-dependent diffusivity on temperature-sensitive-paint heat-flux measurement, International Journal of Heat and Mass Transfer, Vol. 147, 118923.

Liu T, Risius S 2019 In-situ calibration for temperature-sensitive-paint heat-flux measurement on a finite base, International Journal of Heat and Mass Transfer, Vol. 140, pp. 420-425.

Liu T, Montefort J, Stanfield S, Palluconi S, Crafton J, Inverse heat transfer analysis for global heat flux measurements in aerothermodynamics testing, Progress in Aerospace Sciences, 107, pp. 1-18 (2019).

## 8. OpenPhotogrammetry

OpenPhotogrammetry contains specialized photogrammetric and image processing MATLAB functions useful for wind tunnel and other ground-based testing of aerospace structures are described. These functions include single view and multi-view photogrammetric solutions, basic image processing to determine image coordinates, 2D and 3D coordinate transformations and least squares solutions, spatial and radiometric camera calibration, epipolar relations, and various supporting utility functions.

The programs described here should be viewed as complementing rather than replacing standard photogrammetric packages that are used quite commonly for spatial measurements where the images can be acquired in a sequential manner as the camera is moved about the object. Instead the programs were developed for specialized aerospace applications where traditional photogrammetry techniques are often not applicable due to various constraints such as limitations on camera location, limitations on size and mass of the camera, requirement for remote operation, severe limits on setup time due to wind tunnel productivity requirements, and/or the need for near real-time results. The functions serve as building blocks to develop custom measurement systems that may utilize non-traditional photogrammetry for near real-time applications. The functions can be relatively easily customized to further enhance their value in the development of measurement systems for unique and varied applications. In some cases the functions can be utilized within the MATLAB environment for the application. In other cases where performance is critical, the functions can be used to develop the measurement strategy, which can then be implemented in C-code to maximize efficiency. Although the MATLAB Image Acquistion toolbox was not utilized in the current version of the programs, it is anticipated that the coupling of the programs with the acquisition toolbox should provide a powerful developmental platform.

**References:**

Liu T, Radeztsky R, Garg S, Cattafesta L 1999 A videogrammetric model deformation system and its integration with pressure paint, AIAA 99-0568.

Liu T, Cattafesta L, Radezsky R, Burner A W, 2000 Photogrammetry applied to wind tunnel testing, AIAA J. Vol. 38, No. 6, pp. 964-971.

Liu T, Barrows D A, Burner A W, Rhew R D, 2002 Determining aerodynamic loads based on optical deformation measurements, AIAA J. Vol. 40, No. 6, pp. 1105-1112.

Liu T, 2004 Geometric and kinematic aspects of image-based measurements of deformable bodies, AIAA J., Vol. 42, No. 9, pp. 1910-1920.
Liu T, Fleming G, 2006 Videogrammetric determination of aircraft position and attitude for vision-based autonomous landing, AIAA Paper 2006-1437, Reno, January.
Liu T, Burner A W, 2007 Photogrammetry toolbox reference manual, NASA Langley Research Center Contract Report, May.
Liu T, Burner AW, Jones T, Barrow, D, 2012 Photogrammetric techniques for aerospace applications, Progress in Aerospace Sciences, Vol. 54, pp. 1-58.

## 9. OpenPressureFromVelocity

OpenPressureFromVelocity contains Malab functions for extraction of pressure from velocity data. This method is based on a variational formulation with a smoothness constraint for extraction of pressure from two-dimensional velocity field. The Euler–Lagrange equation is obtained to determine a pressure field from velocity data in a domain with suitable boundary conditions. Numerical algorithms are developed to solve the Euler–Lagrange equation with suitable boundary conditions. The method is evaluated on a simulated two-dimensional oblique Hiemenz flow. In an experimental case, pressure fields near a freely flying hawkmoth are estimated from high-resolution velocity fields that are obtained by applying the optical flow method to high-speed Schlieren photography images.

**References:**

Cai Z, Liu Y, Chen T, Liu T, 2020 Variational method for determining pressure from velocity in two dimensions, Experiments in Fluids, Vol. 61, No. 118 (26 pages).

## 10. OpenSurfacePressureFromSkinFriction

OpenSurfacePressureFromSkinFriction contains Matlab functions for extraction of surface pressure from skin friction data obtained by using the GLOF method. This method is used to extract a surface pressure field from a skin friction field in complex flows as an inverse problem, focusing on its application to the GLOF skin friction measurements. This method is evaluated through simulations in the Falkner–Skan flow and the flow over a 70°-delta wing to investigate the effects of the Lagrange multiplier, downsampling rate, noise level, and the value of a constant source term in the approximate method. Further, the approximate method is applied to the skin friction fields obtained by GLOF measurements in the flow over a 65°-delta wing and the square junction flow to obtain the normalized surface pressure fields. The proposed method provides a useful tool to obtain the high-resolution fields of both surface pressure and skin friction by GLOF measurements in complex flows (particularly at low speeds).

**References:**

Cai Z, Salazar D, Chen T, Liu T, 2022 Determining surface pressure from skin friction, Experiments in Fluids, 63:152.