PaIRS-UniNa: a robust and accurate free tool for digital particle image velocimetry and optical camera calibration

G. Paolillo[1,*], T. Astarita[1]

1:Dept. of Industrial Engineering, University of Naples "Federico II", Napoli, Italy
*Corresponding author: gerardo.paolillo@unina.it

Keywords: free software, 2D planar and stereoscopic particle image velocimetry, image deformation, camera calibration, Python.

ABSTRACT

This contribution presents PaIRS-UniNa (PArticle Image Reconstruction Software – University of Naples "Federico II"), a free software application designed to perform digital particle image velocimetry (PIV). PaIRS-UniNa relies on a powerful C library designed for speed, robustness and accuracy, and a user-friendly graphical interface running in Python environment on all operating systems, including Windows, Linux, and MacOS. At the current stage, it features modules to perform two-compenent (2C) PIV, stereoscpic PIV and optical camera calibration for multi-camera systems. The processing of PIV and stereoscopic PIV data is based on an iterative image deformation method, which can be customized by the user varying different parameters in such a way to find the best compromise between accuracy and computational speed for each application. Beyond this flexibility, preset strategies are also available for image analysis and designed for specific tasks like fast visualization of preliminary results or high accuracy. For the stereoscopic PIV process both mapping and warping approaches are available, in conjunction with a dispartiy correction procedure aimed at accurately estimating the laser sheet plane location and correcting errors due to misalignment and inaccurate displacement vector positions. The calibration module (CalVi) supports accurate calibration with the camera models mostly used in the PIV community: polynomials, rational functions and the pinhole camera model. Moreover, it supports the integration of the pinhole camera model with a refractive correction model for cylindrical geometries and camera calibration procedures working with unknown positions and orientations of the calibration target.

1. Introduction

Particle image velocimetry (PIV) is a standard tool in the fluid dynamics community and is widely used for analyzing turbulent flows. Recent advancements in hardware and processing algorithms have significantly boosted the development of PIV methods, enabling time-resolved and 3D measurements at affordable costs and times. Despite this, standard systems using a single camera to measure the two-component (2C) velocity field in a flow domain slice remain practical and flexible, especially for preliminary studies where time is a critical factor or for extensive parametric investigations involving large data volumes. Modern imaging systems provide a wealth of information,

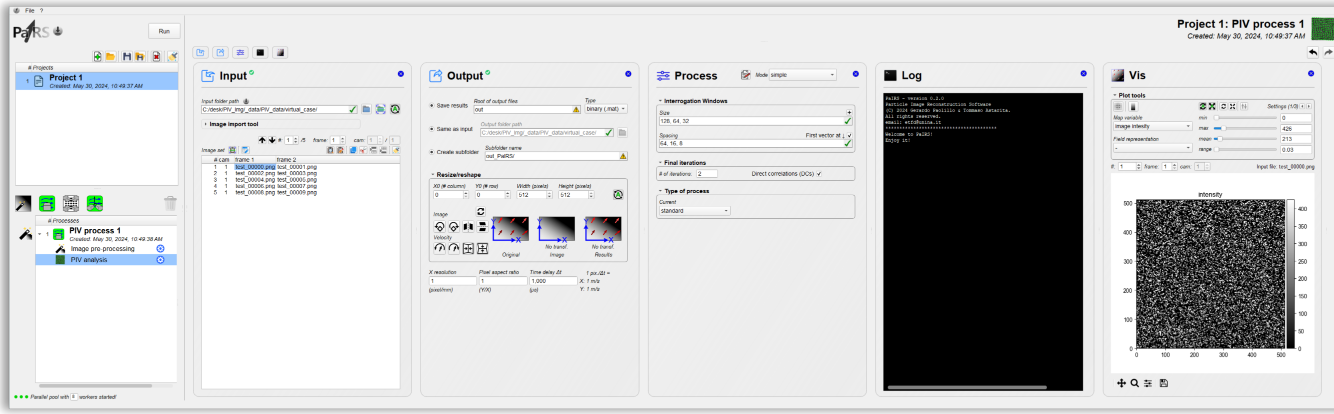

Figure 1. PaIRS graphical user interface.

such as turbulence spectra, space-time correlations of kinematic quantities, particle accelerations, and pressure fields, but analyzing this data is complex and feasible only for specific test cases. On the other side, for planar 2D PIV, the crucial step is image processing, where accuracy and speed of algorithms are fundamental. Several commercial PIV software packages are developed by major PIV system providers, including Dantec, LaVision, MicroVec, PIVTEC, and TSI (Kähler et al., 2016). Additionally, free software options like OpenPIV (Ben-Gida et al., 2020) and PIVlab (Stamhuis & Thielicke, 2014; Thielicke & Sonntag, 2021) are available and widely used in scientific research.

This contribution presents PAIRS-UniNa (PArticle Image Reconstruction Software – University of Naples “Federico II”), a free software application designed to perform digital PIV with the most recent and advanced algorithms available in the literature. PaIRS-UniNa has been developed at the Department of Industrial Engineering at the University of Naples "Federico II" since 2000. Such a development has been driven by the contributions of students and staff from the Experimental Thermo-Fluid Dynamics group, as well as advancements in techniques documented in the literature (Astarita & Cardone, 2005; Astarita, 2006, 2007, 2008, 2009). The software includes various modules for processing of stereoscopic, double-frame, and time-resolved tomographic PIV measurements. PaIRS-UniNa is built on a robust and efficient C library (PaIRS-PIV), designed for speed and accuracy, and features a user-friendly graphical interface developed in Python (PaIRS). In particular, PaIRS-Unina is supported by Python 3.8+ and can run on all operating systems, including Windows, Linux and MacOS. Currently, PaIRS-UniNa offers modules for performing 2D planar and stereoscopic PIV, along with optical camera calibration for multi-camera systems.

2. The user graphical interface

Figure 1 shows the PaIRS graphical user interface. On the left side of the main window, the project tree and the process tree are displayed. Once a project is created, the user may append vari-

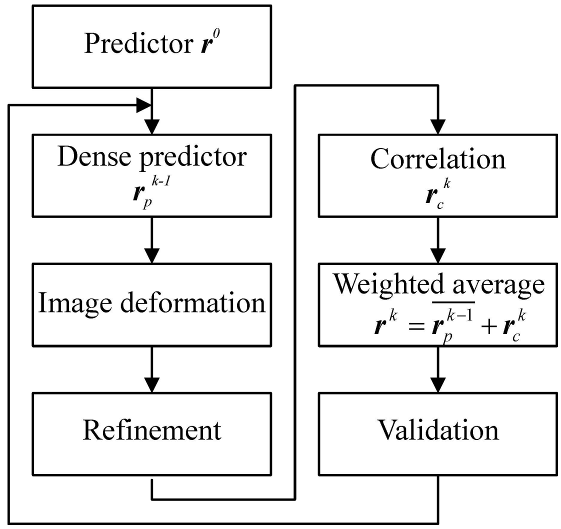

Figure 2. Schematic diagram of the iterative multigrid image deformation method implemented in PaIRS-UniNa.

ous types of processes to the underlying process tree. In the current version of the software, the available processes include: image pre-processing, two-component planar PIV processing, camera calibration and stereoscopic PIV processing. The parameters for each process can subsequently be modified or selected within the tabs that appear on the right side of the window.

Figure 1 illustrates the editable tabs for a PIV process. The Input, Output and Process tabs are used to specify the parameters of the image files and the output files produced by PaIRS (including their full paths) and the settings of the PIV process to be performed. The Log tab is used to visualize output from the PaIRS-PIV library and further error/warning messages, while the Vis tab can help user in visualizing the input images and the results from image preprocessing and/or PIV analyses.

After compiling the list of projects and processes, the user can launch them sequentially by clicking the "Run" button.

3. Iterative image deformation method

PaIRS employs an iterative multi-grid approach based on image deformation. The schematic flowchart of such an approach is shown in Figure 2. In the first step, a predictor displacement field is computed using weighted cross-correlation. The user is allowed to select different types of weighting windows (WWs) among those classically employed for Fourier analysis (e.g., rectangular, Blackman, Gaussian, Harris, Hann) and other proposed in the PIV literature (e.g. Nogueira et al., 2005). In such a way, the user can tailor appropriately the modulation transfer function (MTF) of the PIV process to the specific application under examination.

In the dense predictor step, the predictor displacement field is interpolated to evaluate the dis-

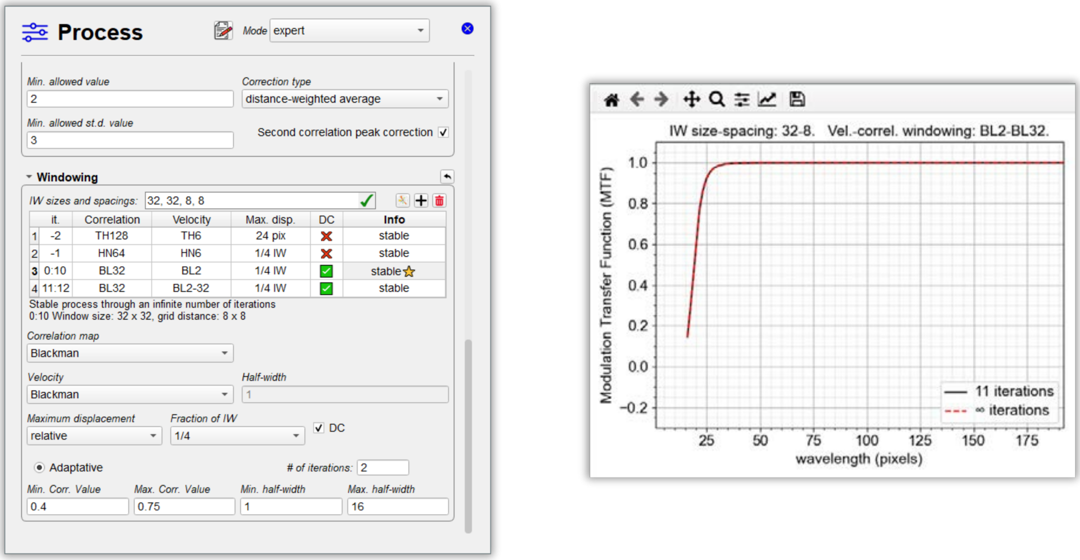

Figure 3. Windowing box in Process tab and representation of the MTF function for a selected IDM.

placement of each pixel of the image used in the following image deformation step. In both these steps, the user can select the type of interpolating function, choosing from different options: bilinear, bicubic, interpolations based on simplexes or on the FFT shift theorem and B-splines of different orders. Therefore, the best compromise between the accuracy of the reconstructed displacement field and computational speed can be reached based on the application requirements.

In the refinement step the user is allowed to change the sizes of the interrogation windows as well as their overlap thus increasing the spatial resolution. Then, the weighted cross-correlation is applied to the deformed images to obtain a corrector field and, in the weighted average step, the displacement at the generic iteration is evaluated by summing this corrector field to a weighted average over a prescribed window of the dense predictor. Also in this case, the WW applied to the dense predictor can also be arbitrarily chosen by the user to customize the modulation transfer function (MTF). Finally, before iterating, a validation of the computed displacement field is performed; also in this step, several strategies can be defined by the user by selecting methods commonly adopted in the literature (such as that proposed in Westerweel & Scarano, 2005).

Figure 3 reports an example of a customized iterative image deformation method defined in the Process tab of PaIRS. Different types of correlation and velocity averaging WWs are employed in such a method (top-hat for the first iteration, Hann for the second and Blackman for the remaining iterations). Moreover, the last two iterations relies on the adaptive approach presented in Astarita (2009). It is noted that, for each iteration of the process, it is possible to select a maximum allowed displacement and whether to use direct correlation calculations. The right side of Fig. 3 depicts the MTF for the final iterations from 0 to 10, which involve 32×32 Blackman correlation windows with 75% overlap and 2×2 Blackman velocity averaging windows.

Beyond the flexibility of PaIRS, which leaves ample room for customization in different setups and applications, the user can also simply choose preset strategies for image analysis, which have been designed for specific tasks like fast visualization of results in preliminary measurements or high accuracy in the final phase of investigation. When opting for these presets, very few parameters must be specified and accurate results can be achieved even by inexperienced users (such as master students dealing with their first experiments).

4. Stereoscopic particle image velocimetry

Stereoscopic PIV data can be processed in PaIRS-UniNa via calibration-based methods. Two alternative approaches are available: mapping (Willert, 1997) and warping (Soloff et al., 1997). In the mapping approach, the PIV process is applied to the de-warped images to obtain the 2D-2C displacement fields along the directions orthogonal to the camera axes. The 2D three-component (3C) velocity field in the laser sheet plane is then obtained by combining the 2C displacements via geometrical reconstruction formulas. In contrast, in the warping approach, the PIV process is applied directly to the recorded images, while the 3C reconstruction and image de-warping are performed in a single step using a gradient-based formulation.

Robust optical calibration of the two cameras employed in a stereoscopic configuration, required for both the dewarping and the 3C reconstruction steps, can be performed in CalVi (Calibration Visualizer), a further module of the PaIRS-UniNa package, presented in the next section. In addition, the stereoscopic PIV module includes also a procedure to estimate accurately the location of the laser sheet plane and correct the errors due to the misalignment between the laser sheet plane and the reference calibration plane and those associated with inaccurate estimation of the positions of the displacement vectors or the local viewing angles in the 3C reconstruction step. Such a procedure (disparity correction) is iterative and implemented following the approaches explained in Wieneke (2005) and Giordano & Astarita (2009), with some improvements based on the more recent work of Wieneke (2018). Information about the laser thickness is also retrieved in this step and provided to the user.

5. Calibration Visualizer

CalVi (Calibration Visualizer) is the module of PaIRS designed for fast and accurate calibration of single and multiple camera bundles in different optical configurations, including both stereoscopic and tomographic systems. CalVi supports accurate calibration with the camera models mostly used in the PIV community: polynomials, rational functions and the pinhole camera model (Willert, 2006). The orders of the polynomial and rational models can be chosen arbitrarily in the software and estimation of the related calibration parameters is performed via fast and robust lin-

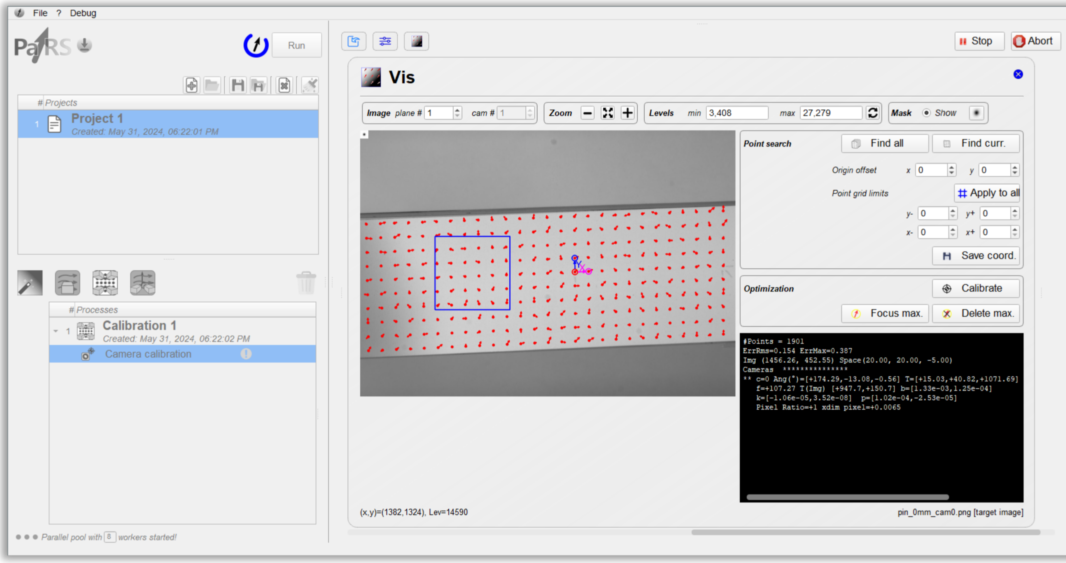

Figure 4. CalVi graphical user interface.

ear least-squares optimization algorithms. The pinhole camera model implemented in CalVi is based on the works of Tsai (1987), Melen (1996) and Heikkila & Silvén (1997) and integrates an implicit lens distortion model Weng et al. (1992). Due to the non-linear nature of the lens correction term, estimation of the pinhole parameters is performed via non-linear optimization methods.

CalVi also supports the integration of the pinhole camera model with a refractive correction model for cylindrical geometries. This correction model implements a ray tracing procedure to accurately represent the refraction of the lines-of-sight (LOSs) across cylindrical interfaces using Snell's law, as detailed in Paolillo & Astarita (2020). Compared to rational and polynomial models (Paolillo & Astarita, 2021), such an approach has several advantages and, in particular, it requires only a small number of calibration parameters, each with clear physical or geometrical significance, and allows for the calibration of cylinder parameters even when the target is placed outside the cylinder.

In addition to the above features, CalVi also performs the estimation of the location and orientation of the calibration target related to a specific image, which are identified by six coefficients (the plane constants). This serves a twofold purpose: on one side, after performing a calibration, the user can identify potential errors in the positioning of the calibration target via an a-posteriori estimation of the plane constants for all the target observations employed; on the other side, the plane constants can be optimized simultaneously with the camera calibration parameters In such a way, during the calibration step, the target may be moved by hand and accuracy comparable to (or even better than) that of a conventional calibration, in which the target is displaced with the aid of translational and rotational stages and knowledge of the target positions is a strict requirement, can be achieved.

CalVi relies on a user-friendly graphical interface (see Fig. 4), in which the user is driven through the different calibration steps, from the selection of the world reference frame to the visualization of the calibration results and refinement of the same via outlier removal.

6. Conclusions

In conclusion, it is worth noticing that PaIRS-UniNa has been validated both numerically and experimentally and its accuracy and robustness have been proved during the 2nd and 3rd International PIV Challenges (Stanislas et al., 2005, 2008). The present code has also been used in tens of experimental studies not only by the Experimental Thermo-Fluid Dynamics group of University of Naples (Greco et al., 2013; Cafiero et al., 2021), but also by collaborating international groups (Sfarra et al., 2013; Raiola et al., 2015). Therefore, PaIRS-UniNa is expected to represent a fast and efficient free alternative to commercial software for PIV analysis in both research and industrial applications.

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