The Future of Engineering Education

2024 Annual Conference & Exposition

Oregon Convention Center
Portland, OR . June 23 - 26, 2024

ASEE

Paper ID #41213

Lab on Cart: Developing a Low-Cost Fluid Visualization Setup for Experiential Learning, Class Demonstration, and Outreach

Alireza Ebadi, Worcester Polytechnic Institute
Prof. Ahmet Can Sabuncu, Worcester Polytechnic Institute

Dr. Sabuncu holds a Ph. D. in Aerospace Engineering from Old Dominion University. Dr. Sabuncu's professional interests spans from engineering education research, history of science and engineering, thermo-fluids engineering, and microfluidic technology.

Work In Progress: Lab on Cart: Developing a Low-Cost Fluid Visualization Setup for Experiential Learning, Class Demonstration and Outreach

Abstract

Despite being present in many natural phenomena and engineering systems, fluid dynamics is often perceived as difficult and mysterious by students. The transparency of common fluids (air and water) and the complex, non-linearity of the governing equations make understanding these dynamics challenging.

Flow visualization has been shown to be an effective method for teaching complex fluid dynamics to a general audience. The streamlines over a car prototype in a wind tunnel, or the vortex formation of a hurricane, to name a couple, have become household images confirming the efficacy of this technique. Contrary to its importance and positive role in learning enhancement, flow visualization is not commonly used in undergraduate fluid dynamics courses. Factors such as the cost of equipment, time-consuming setup, and limited space in wind/water tunnels have kept hands-on fluid-related projects relatively rare at undergraduate institutions.

This project aims to develop a low-cost, safe, and portable flow visualization system, paired with an open-source program. This setup will be utilized for class experiments, student projects, and demonstrations for outreach efforts.

Keywords
Flow Visualization, Experiments, Classroom

1   Introduction

Fluid dynamics is often perceived as one of the most challenging subjects in the undergraduate engineering (Hunsu, Abdul, Van Wie, Adesope, & Brown, 2015). Abstract concepts such as "fluid shear stress" and "turbulence" coupled with challenging partial differential equations (e.g. Navier-Stokes equations) are the main contributors to the complexity of the subject. Consequently, most examples and assignments involve uninteresting problems that are not common in many engineering applications or natural phenomena. Moreover, the transparency of most common fluids such as air and water along with their lack of resistance to strain makes them a non-intuitive medium to teach complex subjects such as conservation of momentum, or viscous momentum transfer (Goodman, Hertzberg, Curran, & Finkelstein, 2015; Streveler, Olds, Miller, & Nelson, 2003). For example, while bending and buckling of a solid object can be easily observed, the turbulence in the air circulated by a fan cannot be observed or readily experienced. In the absence of analytical solutions for most applied fluid dynamics problems, there are two alternatives to better comprehend such dynamics: simulation and experimentation. Flow simulation requires extensive expertise in modeling the flow and the solid domain, and access to commercial license, such as ANSYS Fluent. Besides, it won't offer an interactive experience for the students as they are typically run by an expert and students only observe the results. The experimentation, however,

may require less expertise if the main objective is interactive exchanges and qualitative observations.

One of the oldest and hence, most familiar experimental techniques in fluid dynamics is flow visualization. From stirring cream in coffee, to following the trajectory of a leaf in the wind, most students are familiar with the concept. Despite its importance in comprehending flow dynamics, flow visualization is not commonly utilized in undergraduate fluid courses. Expensive and space-occupying experimental setups such as wind or water tunnels and complementary measurement equipment such as lasers and cameras, hotwire anemometers, pitot-static tubes and tedious experimental setup are among the main reasons that experimental setups are not adopted by many undergraduate courses. For instance, a typical wind or water tunnel will occupy a room and the equipment often cost upwards of tens of thousands of dollars.

Following the long-established practice of project-based learning at their institution, the authors decided to develop a low-cost space-aware particle image velocimetry (PIV) setup for flow visualization. The setup would allow students to experiment with common fluid dynamics and customize the experiments to study the relationship between boundary and initial conditions and those dynamics. The project was inspired by other successful similar implementations at comparable universities in the past two decades (Crimaldi & Knight, 2005; Budd & Howison, 2018; Elliot, Minichiello, & Caldwell, 2021; Minichiello, et al., 2021). For example, Crinaldi and Knight used the 8x1 m^2 water tunnel with an argon-ion laser and a commercial high-speed camera to introduce students to planar laser-induced fluorescence (PLIF), a powerful flow visualization technique (Crimaldi & Knight, 2005). While the experience is valuable, the students would only experience the experiment passively as they did not have the training, nor expertise to interact with the equipment. Budd and Howison utilized an existing water flume and developed a low-cost PIV system for undergraduate fluids laboratories (Budd & Howison, 2018). Elliot *et al.* further advanced the concept of low-cost PIV setup by incorporating readily available equipment such as laser pointers and fish tanks to develop a mobile instructional particle image velocimetry (mI-PIV) learning tool (Elliot, Minichiello, & Caldwell, 2021; Minichiello, et al., 2021). The goal of the present authors was to adapt the previous designs to better suit the objectives of their programs, which are to increase accessibility and improve customizability.

Inspired by the mI-PIV learning tool, the authors decided to create an array of instructional PIV setups to further increase the accessibility and customization of the setup. Adding more setup and dedicating each to a small group of students would enable the instructor to run several different experiments simultaneously, or allow each team to customize a single experiment and then compare the results. Furthermore, the authors utilized a MATLAB library (PIVlab) for data analysis instead of the Android app in the mI-PIV for enhanced control and analysis capabilities and increased accessibility. As a first step, the current study has developed a single instructional PIV and complementary instructional modules as a proof of concept. In the next phase, the authors will develop the remaining members of the array and implement them in their undergraduate fluid dynamics and experimentation classes.

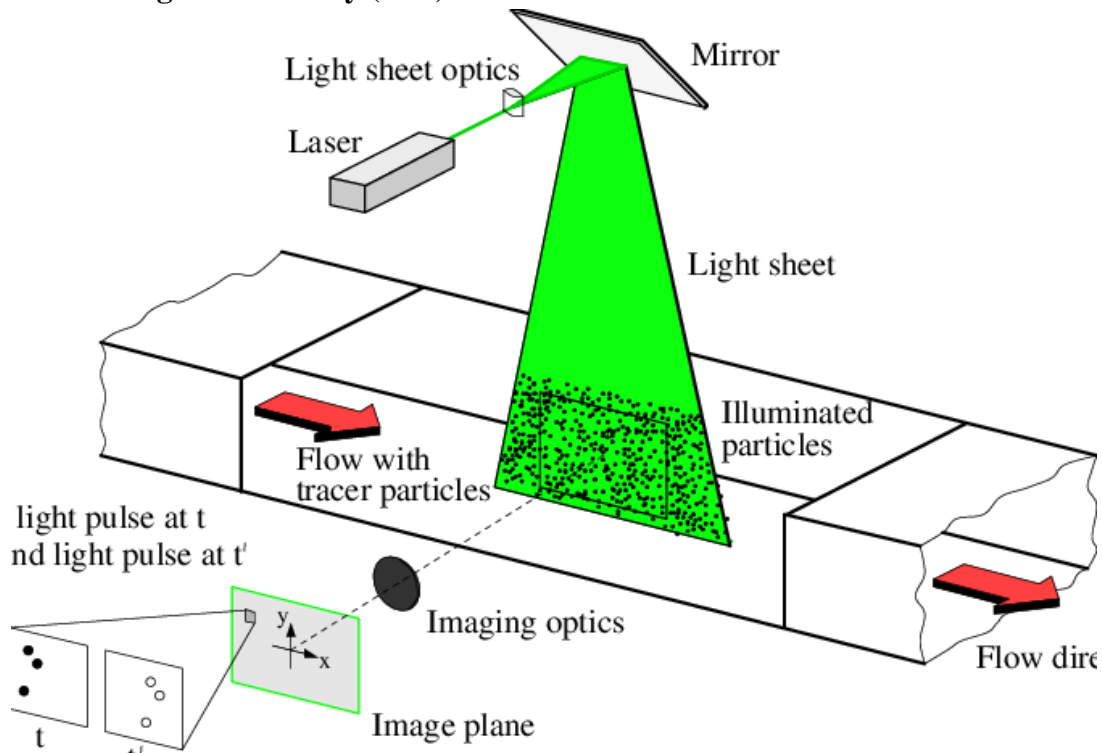## 2   Particle Image Velocimetry (PIV)

Figure 1 - Typical experimental setup for PIV recording in wind or water tunnel (Kompenhans, et al., 2000)

PIV was chosen as the primary flow visualization technique because it is one of the few non-intrusive whole-field flow measurement techniques. It is non-intrusive in a sense that no measurement probe is placed within the flow, and whole-field in a sense that it provides a two-dimensional (or three-dimensional) instantaneous measurement of the velocity field in a planar slice of the flow. The principles of PIV are simple but, in practice, data acquisition can be very challenging. A brief description of the PIV technique is provided here. References are provided for more detailed description (Adrian & Westerweel, 2011; Raffel, et al., 2018).

PIV is a particle-based measurement technique in which the fluid velocity is inferred from measurement of the velocity of tracer particles seeded into the flow. If the inertia of a tracer particle is small and the particle density matches the fluid density, the particle will passively follow the fluid motions. This is the ideal case, but in practice the particle will have finite inertia and a finite density difference relative to the density of the fluid. The PIV technique uses a laser light sheet formed (typically) from a pulsed laser to illuminate the tracer particles in a planar slice of the flow. The pulsed light sheets are separated in time, where the time separation is known and well-controlled. The laser light scattered by the particles is captured on a camera. Cross-correlation techniques applied to a successive image pair provide two components of the velocity vector field in the imaged plane. A schematic of a typical PIV system is illustrated in .
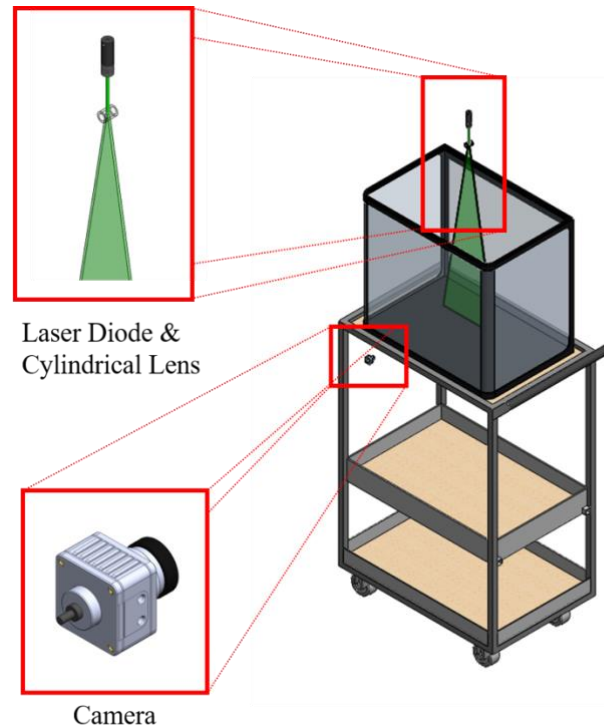
Figure 2 - Lab on Cart Setup

3   Lab on Cart

Following the development of the mI-PIV system **(Elliot, Minichiello, & Caldwell, 2021; Minichiello, et al., 2021)**, we decided to create an array of portable, inexpensive PIV setups. The main differences between the current project and the mI-PIV system are as follows: the current system utilizes MATLAB and the publicly available PIVlab library for data acquisition and analysis, whereas mI-PIV used their developed Android application. Furthermore, the current setup is designed to be replicated in large number increasing its accessibility and enhancing its customizability. The setup consists of a 10-gallon fish tank ($25), a small cart ($81), a USB camera ($77), a hunting laser diode with mounts ($25) and a cylindrical lens ($43), summing to $251. A schematic of the setup is illustrated in Figure 2.

The setup is complemented with an application developed in Matlab to initiate the camera, record images, and process the recorded images to create two-dimensional vector fields using PIVlab (Thielicke & Stamhuis, 2014). The application provides visual instructions and tips for the user to troubleshoot and enhance their processing. A screenshot of the application developed as part of the project is shown in Figure 3. The application has 4 stages, demarked by the four tabs on the left side of the application:

1. Calibration: to calibrate the camera and find the magnification factor, which is calculated as the ratio of the camera image size to the field of view (FOV).
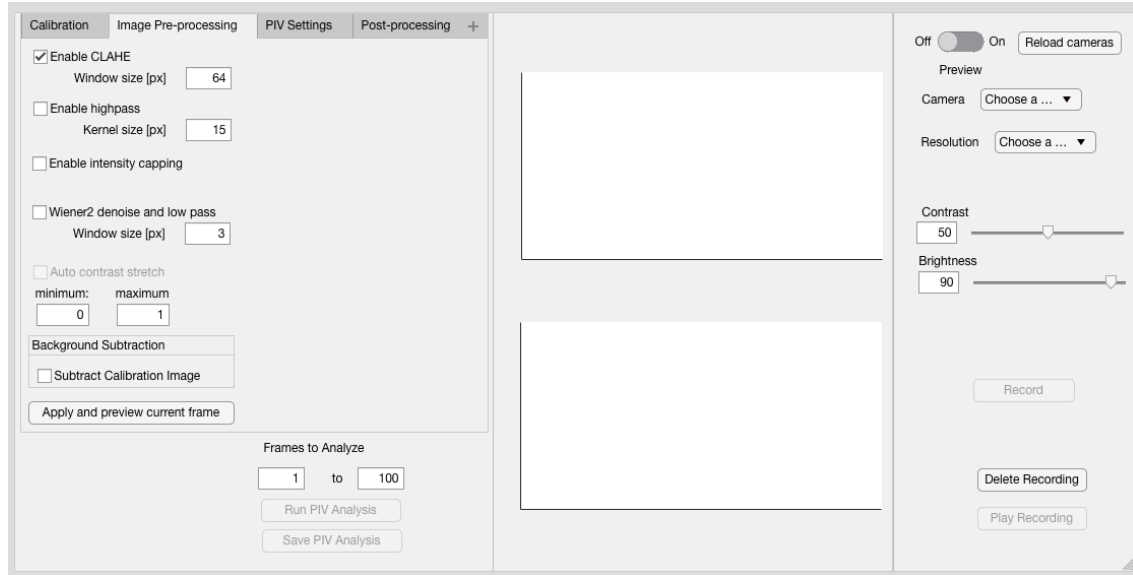
Figure 3 - PIV application developed based on PIVlab.

2. Image Pre-processing: to minimize noise and adjust camera intensity recordings. A side-by-side comparison of a raw image before and after processing is shown in Figure 4.
3. PIV Settings: to set PIV analysis settings such as interrogation area or step size.
4. Post-processing: to either remove outlier vectors or fill gaps in the vector matrix.

An outline of the instruction manual to be distributed to the students is provided in Appendix A.
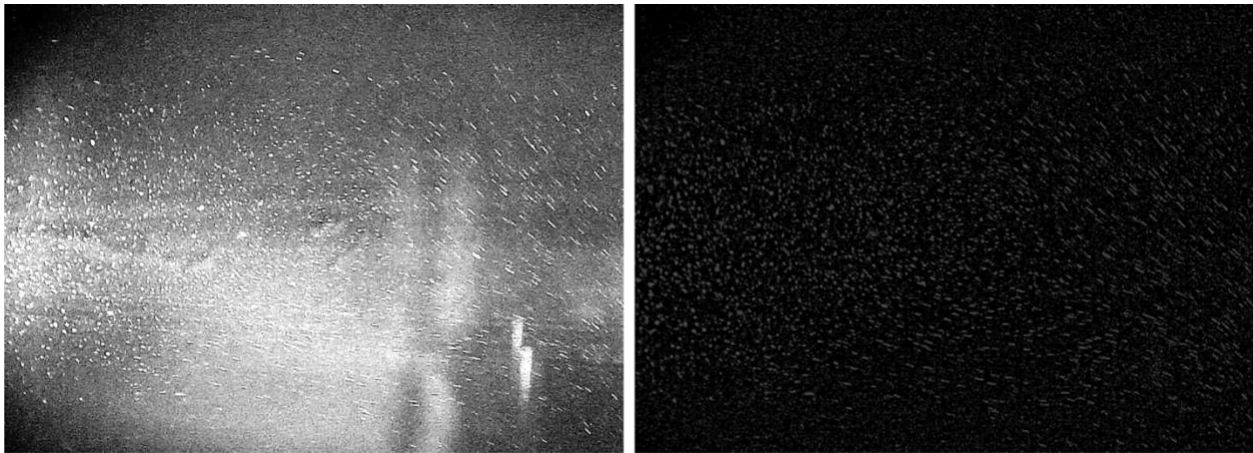

Figure 4 - Raw image before (left) and after (right) pre-processing.

4   Results and Future Work

The initial setup is developed and qualitatively validated. A snapshot of a raw image and the processed vector field is illustrated in Figure 5. The example shows the process of recording the raw images (a), processing them to detect tracer particles (c), calculating the velocity vectors (c), and post-processing and displaying the vector magnitudes (d). The vector magnitudes are
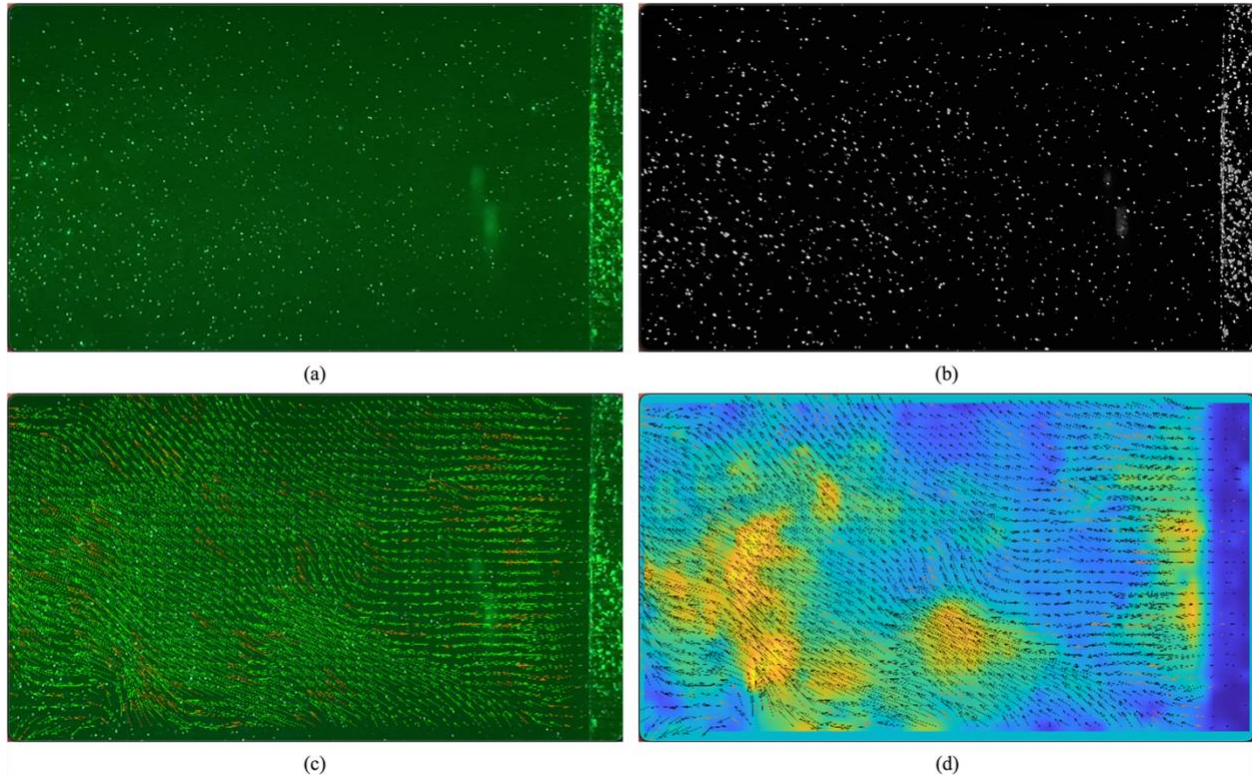
Figure 5 - Sample PIV Results: (a) Raw image, (b) Tracer particles detected, (c) Vector field is calculated, (d) Contour of vector magnitudes displayed.

qualitatively compared with the observed experiment to verify the results are reasonable. The project team is currently fine-tuning the procedure to ensure repeatability. The authors are also designing a series of experiments in which students could observe the flow dynamics using PIV. Sample developed laboratory modules and experimental activities are provided in Appendix B.

A combination of measures will be used to assess students' interactions with the developed setup and the complementary application. The primary measure will be open response questions embedded in the Student Assessment of their Learning Gains (SALG) (Seymour, Wiese, Hunter, & Daffinrud, 2000) survey regarding students' experiences of why they engaged (or did not) with the developed tool, ways in which they found it more useful than the lecture or other materials, and suggestions for improving the tool.

Acknowledgement

Bibliography

Adrian, R. J., & Westerweel, J. (2011). *Particle image velocimetry (No. 30).* Cambridge university press.

Budd, A., & Howison, J. (2018). A low-cost PIV system for undergraduate fluids laboratories. *2018 ASEE Annual Conference & Exposition.*

Crimaldi, J., & Knight, D. (2005). A Laser Based Flow Visualization System For Fluid Mechanics Instruction. *2005 ASSunal Conference*, (pp. 10-46).

Elliot, J., Minichiello, A., & Caldwell, l. (2021). Implementation of a Low Cost, Mobile Instructional Particle Image Velocimetry (mI-PIV) Learning Tool for Increasing Undergraduate and Secondary Learners' Fluid Mechanics Intuition and Interest. *2021 ASEE Virtual Annual Conference Content Access.*

Goodman, K., Hertzberg, J., Curran, T., & Finkelstein, N. D. (2015). Expanding perception: How students "see" fluids. *2015 ASEE Annual Conference & Exposition* , (pp. 26-713).

Hunsu, N., Abdul, B., Van Wie, B. J., Adesope, O., & Brown, G. R. (2015). Exploring students' perceptions of an innovative active learning paradigm in a fluid mechanics and heat transfer course. *The International journal of engineering education*, 1-14.

Kompenhans, J., Raffel, M., Dieterle, L., Dewhirst, T., Vollmers, H., Ehrenfried, K., & ... & Ronneberger, O. (2000). Particle image velocimetry in aerodynamics: Technology and applications in wind tunnels. *Journal of Visualization*, 229-244.

Minichiello, A., Armijo, D., Mukherjee, S., Caldwell, L., Kulyukin, V., Truscott, T., . . . Bhouraskar, A. (2021). Developing a mobile application-based particle image velocimetry tool for enhanced teaching and learning in fluid mechanics: A design-based research approach. *Computer applications in engineering education*, 517-537.

Raffel, M., Willert, C. E., Scarano, F., Kähler, C. J., Wereley, S. T., & Kompenhans, J. (2018). *Particle image velocimetry: a practical guide.* Springer.

Seymour, E., Wiese, D., Hunter, A., & Daffinrud, S. M. (2000). Creating a better mousetrap: On-line student assessment of their learning gains. *National Meeting of the American Chemical Society* (pp. 1-40). San Francisco: National Institute of Science Education, University of Wisconsin-Madison.

Streveler, R., Olds, B., Miller, R., & Nelson, M. (2003). Using a Delphi study to identify the most difficult concepts for students to master in thermal and transport sciences. *2003 Annual Conference* , (pp. 8-1235).

Thielicke, W., & Stamhuis, E. (2014). PIVlab – Towards User-friendly, Affordable and Accurate Digital Particle Image Velocimetry in MATLAB. *Journal of Open Research Software.*

Appendix A – Classroom PIVlab Instruction Manual to Be Distributed to The Students

1   About

This app is meant for use in classroom settings. Based on PIVlab by William Thielicke (Thielicke & Stamhuis, 2014), users can record a video from a USB camera and run a simple PIV analysis on that video. This app was designed in conjunction to a setup which can be easily manufactured in a classroom environment at a low cost.

2   Workflow

The general workflow of Classroom PIVlab consists of setting up the camera, recording the video,

3   Before Running

Before running any experiments using Classroom PIVlab, make sure that you have all the necessary hardware support. This app currently requires the following:

- [MATLAB Support Package for USB Webcams](#) (hyperlink)

- [MATLAB Image Acquisition Toolbox](#) (hyperlink)

- [Image Acquisition Toolbox™ Support Package for OS Generic Video Interface](#) (hyperlink; it might differ depending on the camera being used)

4   Camera Setup

Connect the camera to the computer through a USB cable. With the app open, turn on the preview and choose the camera and resolution that you wish to use. If the camera does not show up, try using the Image Acquisition Toolbox to troubleshoot.

Using the preview window in the middle screen, focus the camera on the particles in the tank. This can be made easier by placing an object stick in the laser sheet and focusing on it. Once the camera is focused, change the contrast and brightness until the most particles can be seen while keeping the image noise to a minimum. At this point, the camera is ready to record.

5   Recording

When ready to record, press the record button in the bottom right of the screen (Note: this button will only be enabled when the preview window is on). It may take a second to start recording, but you will know it is recording once the "Record" button changes to a "Stop" button. Hitting the "Stop" button will end the recording and save the images into a folder to be used by the PIV analysis. Make sure to only click "Stop" once as clicking it a second time will start a second recording.

With the recording finished, a preview of individual frames will show up on the lower window of the app. These can be cycled through with the slider below the record button. The recording can also be deleted with the delete recording button.

6   Analysis

To start the analysis, go to the pre-processing tab. With the default settings, apply the pre-processing to a few frames and check the output. If the noise level is low and only particles can be

seen, you can start the analysis. Try different pre-processing settings until the recording only shows the particles and no noise is shown as this will mess up data.

With the pre-processing set up, choose the interrogation area, step size, and whether multiple passes will be conducted. By default, the interrogation area is 64 pixels, but, depending on the resolution of the image and the density of particles, this may be different for your setup. In general, there should be roughly eight particles within the interrogation area (shown as a green square) and the particles should not move more than a quarter of the interrogation area from one frame to another.

Finally, there is the post processing step. This will lower the amount of noise and stray vectors that show up in the analysis.

Once the PIV analysis settings are complete, run the analysis on a few frames by choosing the start and end frames of the analysis. Check if the analysis of these frames looks correct by navigating to them using the slider. Change the analysis settings and rerun the analysis until you get the desired results. Then run the full analysis.

With the analysis done, you can view individual frames using the slider on the right, and you can save the analyzed video as a ".avi" using the "Save PIV Analysis" button.

Appendix B: Potential Course Activities

A Potential Experimental Activity and Learning Modules for Use in Fluid Mechanics

Learning Outcome: Students will be able to learn to analyze and test a physical phenomenon, collect data, study the results, and compare them to theory.

Context: The physical properties, kinematics, and domain geometry of the flow (i.e., its viscosity, velocity and a characteristic length scale) influence the flow phase (laminar or turbulent) and hence, its dynamics.

Procedure: An L-shaped pipe will be constructed with a valve on one end. The pipe, with the valve closed, will be placed in a tank so that the valved outlet is submerged in water and the open end is above the water. The pipe will be filled with water and tracer particles. The students will be surveyed to predict the flow dynamics when the valve is opened. The valve will then be opened and the water discharge into the tank will be illuminated by a laser sheet and recorded by a camera.

Student Deliverable: A 2-page report that describes their observation of the flow discharge into the tank, and answers the following questions:

1. How did the results compare with your expectations?
2. How does increasing the pipe diameter affect the jet dynamics?
3. How does increasing the water column in the pipe change the jet dynamics?
4. What is one other factor that would affect the results?
5. Can you identify different behavior in different segments of the water jet?

A Potential Experimental Activity in Experimentation

Learning Outcome: Students will be able to measure the influence of turbulence and flow separation on hydrodynamic drag characteristics of bluff bodies.

Context: The geometry and surface texture of bluff bodies are engineered to alter its hydro- and aerodynamic characteristics. For instance, golf balls have approximately 300 dimples on them to transition the flow into turbulent regime. Golf balls flying in turbulent regime experience less aerodynamic drag.

Procedure: In a 2-hour activity during The Experimentation laboratory, students will be given means to create different geometry and texture bluff bodies. This will be achieved using clay to make bodies and sandpaper to create different surface roughness. Students will use the flow system developed here to visualize flow and measure velocity vectors. Students will design a low drag system (instructor will determine a quantitative target) utilizing the materials available in the laboratory. Students design selection will be guided by the flow measurements that they acquire.

Student Deliverable: A concise 1 page report that summarizes the use of measurement in the design of a fin. Results to support the outcome of the design.