Work in Progress: Mobile Instructional Particle Image Velocimetry for STEM Outreach and Undergraduate Fluids Mechanics Education

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Work in Progress: Mobile Instructional Particle Image Velocimetry for STEM Outreach and Undergraduate Fluid Mechanics Education

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Introduction

In this paper, we describe a design-based research project to realize, implement, and assess a mobile instructional PIV (mI-PIV pronounced “my-P-eye-V”) system for educational use using an iterative development process. The purpose of mI-PIV is to provide low cost educational access to state-of-the-art fluid flow measurement and flow visualization tools to increase student’s interest, retention, and technical capacity in the broad yet critical field of fluid dynamics. The motivation for mI-PIV is based on the knowledge that a robust understanding of fluid mechanics—the fundamental science of fluid motion—is foundational within fields of vital importance to our nation’s infrastructure, safety and defense, including aeronautical, biological, civil, mechanical, naval, and ocean engineering.

Despite their critical importance within postsecondary engineering education, fluid mechanics concepts are rarely, if ever, introduced during high school. In college, even the most basic courses in fluid mechanics tend to focus on mathematical problem solving, instead of hands-on experimentation, visualization, and measurement using authentic tools and practices. Research has shown that, due to this mathematical focus, common undergraduate fluids courses fail to excite key aspects of student engagement—including internal motivation, interest, and curiosity—that can be awakened through the visual exploration of authentic and aesthetic fluid flows [1]. Not surprisingly, engineering undergraduates often characterize introductory fluids courses as mathematically onerous, conceptually difficult, and aesthetically uninteresting. Undergraduate courses in fluid mechanics, in fact, have been shown to act as curricular gatekeepers to fluids-related studies and careers [2].

In this project we aim to iteratively develop, implement, and assess a low cost, handheld, mobile PIV tool within in high school and undergraduate educational contexts. We anticipate that use of this device will excite student interest in fluid mechanics and increase retention within engineering by supporting conceptual understanding in fluid mechanics courses through hands-on learning.

Background

Laboratory PIV

Traditional Particle Image Velocimetry (PIV) is a powerful laboratory technique used to measure and visualize flow fields that have been seeded with neutrally buoyant particles. In PIV, seed particles are illuminated using high-energy pulsed lasers and digitally imaged; digital image pairs

are then cross-correlated to compute a velocity field that maps the flow of the fluid [3]. PIV was initially developed as a method for visualizing complex flow sub-structures occurring within mathematically indeterminate, turbulent flows that are otherwise invisible to the naked eye. Aided by fast-paced technological advancements in many technologies including digital imaging, computer processing hardware, and high-energy laser design, PIV has become widely accepted within many scientific communities as a robust method for accurately measuring and visualizing flow field dynamics. Along with unparalleled flow measurement and visualization capabilities, laboratory PIV systems are known to be dangerous and expensive due to the need for high energy lasers, precise imaging optics, and proprietary computational algorithms. As a result, expense, size, and safety concerns have limited application of PIV systems within educational settings.

In its current, “modern” form, PIV is described as the “accurate, quantitative measurement of fluid velocity vectors at a very large number of points simultaneously” [4]. PIV offers substantial advantages over “point” or probe-based flow measurement techniques (i.e., vane anemometry, pitot probes, hot wire anemometry, and laser doppler velocimetry) that were used previously [3]. Today, many laboratory PIV systems consist of only two components: a high-energy pulsed laser (equipped with a timing unit and a cylindrical lens that spreads the laser light into a thin “sheet”) and a digital camera (Figure 1).

Figure 1. Two-component laboratory PIV system consisting of a laser with a cylindrical lens and digital camera. The laser is fired in the horizontal direction and spreads into a sheet in the vertical direction. (Smith & Neal, 2016) Used with permission.

The laser sheet illuminates small, neutrally buoyant particles in the flow field for imaging by the camera. PIV software algorithms use cross-correlational analysis to process the time-dependent particle image data pairs and generate two-dimensional vector maps of fluid velocity, as well as compute and map other flow parameters that can be mathematically derived from flow velocity

measurements (e.g., vorticity). As a measurement technique, PIV remains a robust area for research; ongoing advances in imaging technology, laser hardware packaging, and algorithm development continue to enable researchers across many disciplines to use and expand the capabilities of PIV.

Educational PIV

Only a few educational PIV systems exist [5]–[9]. Current educational PIV systems have three major drawbacks: (1) they lack physical mobility, (2) they require network connectivity for data processing and (3) the flow fields are often not adjustable or visible to students. One system, ePIV [7], developed for use in undergraduate course work, consists of a table-top opaque box connected to a computer that displays output from PIV taken inside the setup. Other systems that utilize high-resolution smartphone images require processing on a nearby computer with proprietary software [8], [10]. mI-PIV is a novel fully mobile system that encourages students to visualize fluid flows through experimental, observation and analysis.

Methodology

This project uses a design-based research (DBR) approach for iteratively developing, implementing, and assessing a mI-PIV system. DBR is characterized by being situated in a real-life educational context, focusing on the design and testing of a significant intervention, and using multiple iterations. The first two criteria ensure that the research results can be used to assess and improve educational practice within this, and likely similar, contexts [11], [12]. The iterative process of DBR makes this research method similar to the classical engineering cycle in that it begins with a challenge or question within an educational context, researchers develop a hypothesis, then design and test an intervention or product [13], [14]. That intervention is then evaluated within the educational experience and further refined through subsequent iterations (**Figure 2**).

Implementation will occur in undergraduate fluids engineering courses at Utah State University and the University of Colorado, Boulder and in STEM outreach events for diverse high school student at the Undersea Technology Apprentice Program (UTAP) hosted by the Naval Undersea Warfare Center (NUWC) in Newport, RI, and the GEARUP Summer Engineering Camp funded by the Department of Education and hosted by Utah State University. Students in all settings will work through semi-structured mI-PIV exploratory sessions. Feedback and assessment data will be gathered during these events via self-report surveys, direct observation of student interaction with the mI-PIV tool, and student design and analysis artifacts produced while using the tool. Upon collection, assessment data will be analyzed and used to guide tool improvements during the next design iteration.

mI-PIV Development

Design requirements

The requirements for the successful mI-PIV design include: (1) a freely available, open source app available for download, (2) an easy to use and aesthetic guided user interface intended for use by students with no prior knowledge of PIV, (3) output flow field measurement accuracy within an appropriate margin of error for educational use, (4) easily accessible and low-cost subcomponents to allow for broad educational implementation, (5) required use of LED or low power laser continuous light source to allow for safe yet adequate flow field illumination, (6) straightforward and low cost construction of fluid flow demonstration experiments for use in high school and undergraduate classrooms, and (7) online curricular materials to support exploration of fluid dynamics within a variety of educational environments. A mI-PIV user would hold a handheld laser/LED light source while their mobile device captured and processed images for flow visualization and velocity measurements (**Figure 3**)[15].

Figure 3. Schematic of mI-PIV use. The student illuminates the flow field while her mobile phone captures images and processes them for flow visualization and velocity measurement. (Smith & Warner, 2014) Used with permission.

Design tradeoffs

In designing mI-PIV, there are some inherent tradeoffs to be made compared to an industrial PIV setup. The most important design alteration is the use of low-power continuous lasers or LED laser pointers to illuminate the flow field in place of high-powered pulsed lasers. LEDs offer a widely available, safe alternative to the expensive lasers common to industrial PIV systems which is critical for implementation in high school and undergraduate contexts. One limitation that comes from using LEDs or low-powered lasers is reduced accuracy in the PIV vector field. High accuracy using industrial laser setups comes from rapid laser pulses illuminating the flow field while a high-speed camera images in sequence. Pulsing a low power light source results in diminished brightness that precludes adequate particle illumination for PIV processing. While the use of a continuous, low power light source reduces the accuracy of PIV output, it provides the necessary low cost, safe, and portable light source with adequate accuracy for implementation within educational settings.

Another tradeoff is the PIV analysis itself. Industrial systems use proprietary software and algorithms to process flow field images that are unavailable for educational use. Currently, mI-PIV is based on openPIV, an open source Python PIV algorithm that resides on a remote server. Images taken on a mobile device are transmitted to the server where they are processed, then a vector field is returned to the user. In the future, use of Java based JPIV may allow the application to perform PIV calculations directly on the phone with no need for server transfers.

Results/Progress to Date

1. Application: OpenPIV, an open source PIV algorithm in Python, has been adapted and installed on a Google Pixel 3 Android phone. The application currently allows for image pair upload, server transfer, and retrieval and display of calculated vector field
2. Guided User Interface: A preliminary GUI storyboard has been designed. In this design, users can choose to upload or take an image pair of a flow field, send the image pair to the processing server, and receive a vector field of the flow profile on their device (**Figure 4**).

3. Light source: A green 5 mW continuous laser pointer mounted perpendicular to the flow field is currently being used to illuminate the neutrally buoyant seed particles in the test flow field. This laser pointer was chosen for its low power, low cost and safety for educational use. Together, the light source and mobile data analysis make up mI-PIV which can be used to evaluate flow in student laboratory experiments. These experiments would ideally be: (1) low-cost, (2) constructed with commercially available materials, (3) mobile within a lab setting, and (4) representative of real-world flow profiles.

4. System Testing: Our current test system includes a small aquarium water pump inside a 20-gallon tank pumped water seeded with neutral density PIV particles through a series of PVC tubing to enter the flow visualization window vertically (**Figure 5**).

Figure 5. Experimental mI-PIV flow setup with a recirculating pump and vertical outflow (PVC pipe on right).

The 5 mW light source was held stationary near the tank wall while a mobile device (Galaxy 8) on a tripod perpendicular to the light source captured images of the flow at 30 frames per second. These images were processed using PIVlab, which uses a similar algorithm to the one used in OpenPIV. The calculated vector field using the mobile PIV system was compared to the vector field created from images captured using an industrial PIV system with a high-powered pulsed laser (max 150 W) and high-speed camera (1,000 frames per second) and analyzed in PIVlab (**Figure 6**).

Figure 6. Top: Illuminated particles in flow field using handheld continuous laser (left) and industrial PIV system (right). Image pair not shown. Bottom: PIV analysis of illuminated particles using MatPIV (left) and DaVis (right).

Both analyses showed laminar flow from the output nozzle moving through a relatively stationary surrounding medium. Absolute error was calculated for the mobile phone analysis using the industrial PIV system as a standard with

$$Abs. Error = \sqrt{(u_{phone} - u_{high\ speed\ cam})^2 + (v_{phone} - v_{high\ speed\ cam})^2} \quad (Eq. 1)$$

where u is velocity in the x-direction calculated using images from the mobile phone and high-speed camera and v is the velocity in the y-direction calculated from images using the mobile phone and high-speed camera. Overall, the difference between the mobile phone and the high-speed camera setup is low (max error less than 0.2 m/s) (**Figure 7**).

Conclusions

We completed a preliminary proof of concept of a mI-PIV device that will be refined for implementation in classrooms in both high school and undergraduate levels. Our PIV tool is inexpensive, designed using open access image analysis code, and fully mobile. We anticipate that student users will gain a better understanding of fluid concepts through flow visualization and develop an increased interest in fluid related fields. Future design iterations include fully mobile processing without the use of a remote server and additional flow experiment designs for educational use.

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