<u>Development of a Low-cost Real-time Particle Image Velocimetry System</u>

B. Tech Project Report

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Date: April 24th, 2024 **Naveen Pareek**
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ABSTRACT

In the last few decades, Particle Image Velocimetry (PIV) has been widely used for measuring fluid flow field. Much research has been done in PIV and much research in the direction of making PIV setup cost effective to make it available for undergraduates for research. This paper is a summary of understanding of this research. In this report, we used multiple laser pointers for illumination system instead of a single high-power laser. This reduces the cost as well as reduce harm caused by lasers on humans when get exposed. We also worked on getting insights about cross correlation image processing technique in our last phase study.
Although this work needs some future work, we tried to make a working model. Our aim was to develop a full working PIV setup which can be used for beginners.
We will try to continue this research and make more attempts to reduce costs in image processing setup in future.

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CHAPTER-1
INTRODUCTION

The dream of experimental fluid dynamicists is to be able to measure complex, three-dimensional turbulent flow fields globally with very high spatial and temporal resolution. While we are still far from fully realizing this dream, significant progress has been made towards this goal during the last five decades. Early quantitative measurement methods using Pitot tubes, Venturi tubes and later measurement methods, such as Hot Wire Anemometry (HWA) and Laser-Doppler Anemometry (LDA), by their nature, were measurement methods that provided instantaneous velocity signals at single-points through time (see Figure 1.1 and Figure 1.2).

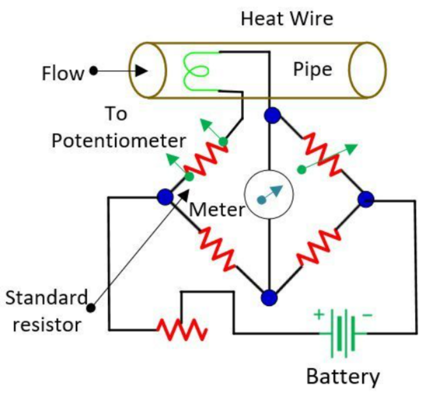

Fig. 1.1 Hot Wire Anemometry Apparatus [1]

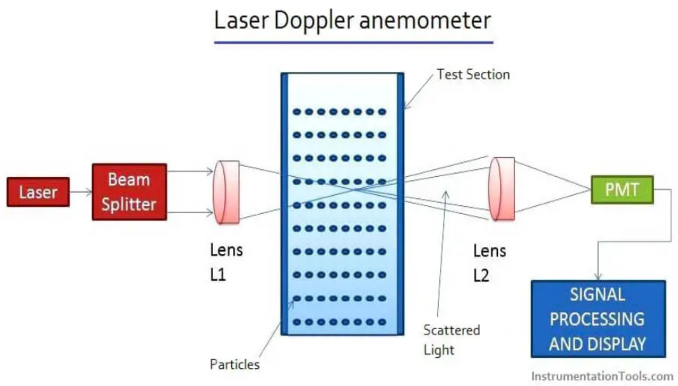

Fig. 1.2 Laser Doppler Anemometer [2]

Early emphasis in turbulence research and its theoretical advancement necessitated a statistical description of turbulent flow fields, which relied heavily upon measurements provided by these single-point measurement techniques. Though useful, these statistical single point descriptions could not give us a clear instantaneous picture of what the fluid was doing globally, and how its instantaneous physics ultimately resulted in the fluid's statistical behavior.

Since the early seventies, the discovery of the existence of three-dimensional coherent structures within turbulent flows using qualitative flow visualization methods (i.e., shadowgraphs, Schlieren systems, dye injection, etc.) has been of significant interest for turbulence researchers. While flow visualization techniques have been around since the days of Prandtl, it is only recently that the advent of modern imaging, laser, and data acquisition technology has allowed for qualitative flow visualization to become quantitative. These advents have allowed for the development and advancement of a relatively new measurement technique, Particle Image Velocimetry (PIV), specifically its digital implementation, which

allows for the global measurements of two component velocities within a two-dimensional domain through time. Because of its ability to provide global two-dimensional kinematic information as well as its ability to map the evolution of coherent structures through time, PIV has become a powerful tool in studying, understanding, and modeling fluid flow behavior.
Particle image velocimetry (PIV) is a measurement technique to instantaneously quantify a flow at high resolution by determining the displacement of many particles that are assumed to follow the flow.

1.1 Apparatus of Particle Image Velocimetry

PIV setup consists of five components: (a) a flow seeded with tracer particles; (b) a light source to illuminate the particles; (c) one or multiple cameras to image the location of the particles; (d) a timing unit to synchronize cameras and light source and (e) a system to store the images.

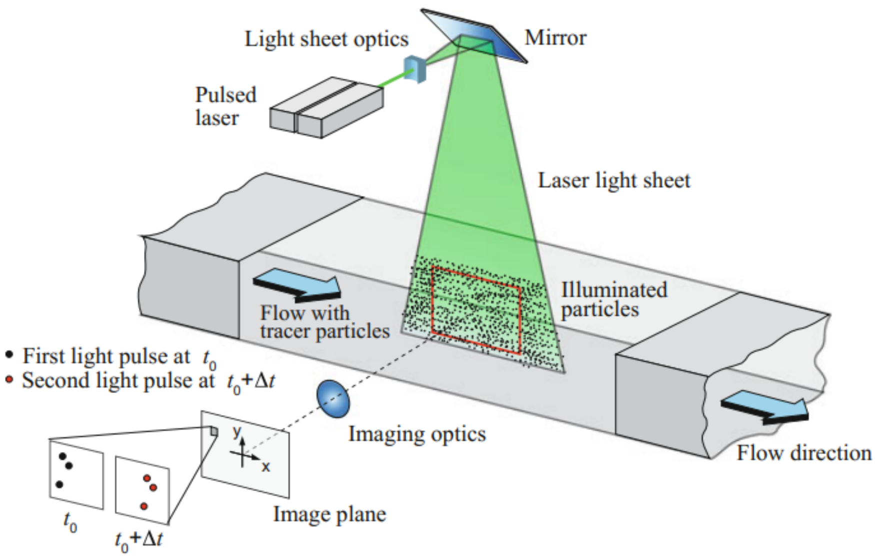

Fig. 1.3 Apparatus of Particle Image Velocimetry [1]

The first PIV systems used film cameras, and it was thought that digital processing was not even possible. The method came into its own in the early 1990s as digital image analysis became a reality and cross-correlation analysis eliminated ambiguity in the flow direction in the data. Up until that point, cameras were not fast enough to acquire two images in close succession. As an alternative, both images were captured on a single exposure. The velocity can still be determined from these images using autocorrelation, but there is directional ambiguity since the software has no way of knowing which particles are from the first or second exposure. Since that time, PIV has grown into a mature experimental method capable of mapping three-dimensional velocity fields from a plane of measurement or an entire volume. While increases in digital photography capability have greatly enhanced what is possible with

PIV, it has also driven costs up. Similarly, software to analyze images captured on several cameras to produce three-dimensional velocity fields has gotten increasingly expensive. It is not uncommon to see the cost of a commercial PIV system start in the six figures. For student laboratory use, this is prohibitively costly. Most of the components required for a basic PIV system can now be purchased separately for only a few thousand dollars total. There are also several open-source computer codes to analyze the images.

Particle Image Velocimetry (PIV) is a non-intrusive measurement that utilizes a predefined laser plane to illuminate tiny particles dispersed throughout the fluid in quick succession. The change in particle position between successive images can be used to determine the velocity of each particle in the images and therefore provide an estimate of the flow field over the entire imaging area.

1.2 Applications of Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV) is a technique used in engineering research to measure flow velocities. Unlike other methods that measure velocity at a single point, PIV can capture the entire flow field, providing two-dimensional or three-dimensional vector fields.

1. Dam-Break Flows

Dam-break waves (DBW) studies are crucial for managing river and coastal areas and assessing flood risks. PIV helps in understanding flood dynamics by accurately estimating flow velocity, flood arrival timing, and potential depth. Innovative techniques combining Sensor Signal Capture (SSC) and Imaging Systems (IS) with PIV have been developed to model dam-break phenomena effectively.

2. Biogenic or Biologically Important Flows

PIV is valuable in studying flows generated by animals due to its non-intrusive nature, minimizing disturbances. It aids in understanding flow dynamics in the benthic zone, although its application depends on the tolerance of organisms to seeded particles and laser illumination.

3. Motion of Blood Cells in a Micro-Channel

In biomedical research, PIV is used to study the motion of blood cells in micro-channels. Understanding the behavior of red blood cells is essential for describing blood flow in the circulatory system. Techniques such as confocal laser scanning microscopy and micro-PIV help in observing and measuring blood flow dynamics.

4. Aerodynamic Research

PIV is extensively used in aerodynamic research to analyze unsteady velocity fields, especially in wind tunnels. It provides valuable data on flow dynamics, particularly in studying helicopter rotor aerodynamics and wake vortex measurements. Advancements in electronic imaging have made PIV data acquisition faster and more efficient.

5. Transonic Flows

PIV is employed to investigate transonic flow fields, particularly in bluff cylinders. It helps in understanding flow structures and velocity distributions, especially in areas with shocks. By comparing tracer particle velocities with fluid velocities, PIV provides accurate insights into flow field dynamics.

1.3 Advantages and disadvantages

This technique has the **advantage** of providing measurement over a (possibly) large area in a short period of time. The **disadvantages** are the cost of the equipment (cameras can cost upwards of $10,000 apiece and lasers routinely cost $40,000 and up) [3], the need for optical access for both the cameras to image the flow and for the laser. One of the greatest disadvantages of modern, high-speed PIV systems is that they rely on high-power lasers. Such laser systems pose a health and safety risk to their users and to their surroundings as they can damage tissues, cause skin burn, or in extreme cases, lead to the loss of sight.

This paper is an attempt to develop a setup of a development of a low-cost real-time particle image velocimetry system, suitable for use in undergraduate laboratories and beginners.

CHAPTER-2
LITERATURE REVIEW

2.1 Attempts towards development of cost-effective PIV systems:

Bhakta [2] conducted a series of experimental tests to compare the multiple diode laser apparatus (a multiple-diode laser system consisting of continuous lasers allows for flexible high-speed imaging with a wider range of test parameters) to a standard Nd:YAG double-pulsed PIV laser. Steady flow testing was performed in a free jet to compare the two systems and validate the accuracy of the multiple laser design. Unsteady flows generated by RP-2 detonators were examined to evaluate the limits of the design's capabilities for recording high-speed, time-resolved data. Steady flow PIV results indicate good similarity between the two laser systems. Unsteady flow testing revealed a camera limitation of 10 microsecond exposures. The key technical obstacle to this approach was laser design and calibration.

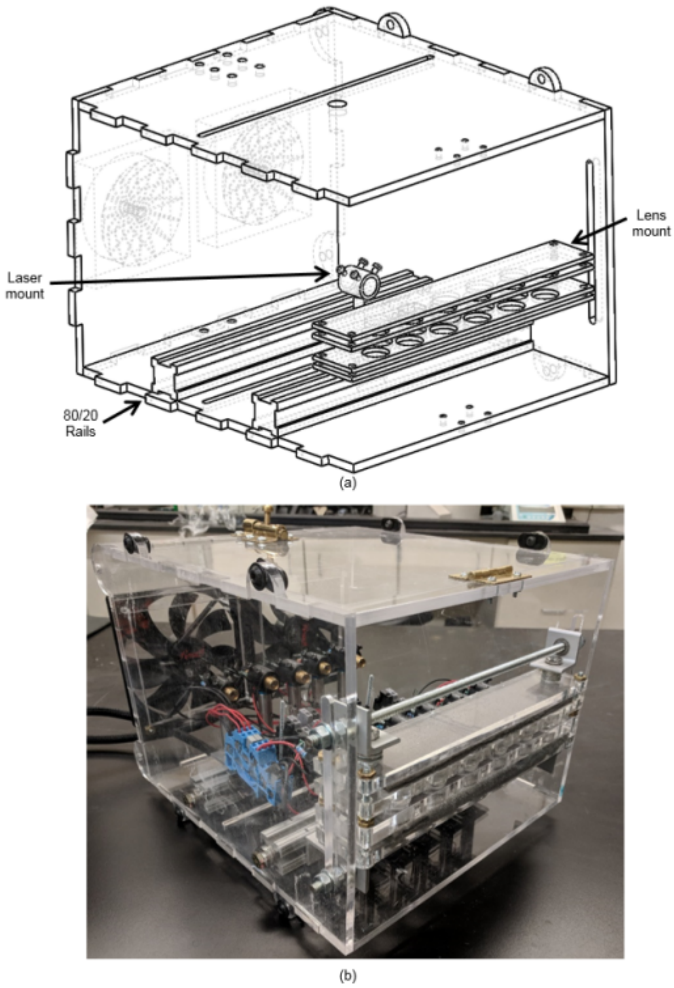

Fig.2.1 (a) Multi-diode laser apparatus schematic [2]   Fig.2.2(b) Completed MdL design [2]

Nader et al. [4] developed a low-cost PIV for fluid-flow measurement and studies of flow around structural models or industrial facilities in wind tunnels. The analysis was conducted in a 100mm X 150mm optical window. The results show that the PIV prototype is working even though further development was necessary. This paper also showed the possibility of a low-cost PIV using a laser-diode with 800 nm wavelength and 100 W rated power as a light source. The results obtained with this PIV show the advantages of the use of this optical technique to measure fluid flow.

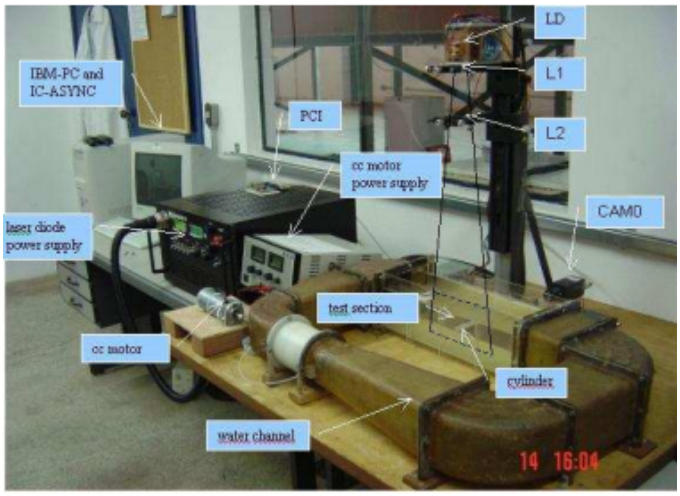

Fig. 2.3 Proposed PIV setup [4]

Ring and Lemley [3] focused on the details of creating a cost effective and portable PIV system that can be simply set up and used in undergraduate research and education. They showed that by tailoring a system to a particular type of fluid flow the cost can be minimized. Fluid flow in ducts can be characterized as laminar, turbulent, or transitional. The flow type is dependent on a dimensionless quantity known as Reynolds number.

$$Re = \rho v d / \mu$$

Where, ρ is the fluid density, v is the fluid velocity, d is the hydraulic diameter (necessary to use for noncircular cross-section duct flow) of the duct, and μ is the fluid viscosity. At relatively low Reynolds numbers (lower than roughly 2100 for a circular cross section) fluid flow tends to be laminar, meaning the flow stays in parallel layers that do not cross. In other words, there is no crossing of streamlines. Higher Reynolds numbers result in transitional flow or turbulent flow. They also proposed followed low-cost PIV model:

Table 2.1 List of all the components proposed with respective amounts.[3]

NOVA laser X100 Compact Laser Pointer	$229
NOVA laser X-Series Holder and Optics Kit	$23
Casio® Exilim HS Ex-ZR100	$299
MATLAB ®	$100
PIVlab©	$ 0
Avidemux ©	$ 0
Acrylic	$10
Dolica 620B100 Tripod	$38
AAA Batteries	$10
Total	$709

Budd and Howison [4] employed a low-power, constant laser light source to reduce cost and maintain lab safety. An open-source analysis code is also used to minimize cost. In working lab exercises with this system, students will understand the PIV data acquisition process, apply MATLAB to analyze the data, and explain the observed flow features. Details of the system are provided so that others may construct a similar system for use in their laboratory. Sample results for flow over a cylinder inside a water flume are included as a demonstration of the system.

Table 2.2 List of Components with respective cost proposed by Budd and Howison [4]

Item	Quantity	Cost
Casio EX-F1 Camera	1	$700
Laserglow Technologies Low-Cost DPSS Laser 532 nm Wavelength	1	$699
MATLAB (student license)	1	$100
PIVLab	1	$0
Cospheric Fluorescent Red Polyethylene	1	$149
Microsheres 0.995g/cc 10-90um – 10g Light sheet Optics	1	$482
Laser Safety Glasses	1	$156
Total	7	$2286

2.2 Attempts towards development of user-friendly PIV systems:

Hochstein et al. [5] showed that since the standard measuring equipment applying a laser system is very sensitive with respect to transport, temperature, humidity as well as laser safety requirements have to be adhered, the observation and classification of flow pattern around human swimmers in swimming pools has been rarely applied. There is a need for a simple, powerful, affordable, robust, and portable illumination source which shall not harm the swimmer by exceeding the permitted maximum radiation for human skin and eyes. As a result, they demonstrated an alternative light source system based on LEDs which enables PIV measurements around human swimmers like experiments with a (traditional) laser system. As an example, the flow fields of two different swimmers with a similar movement and phase are compared using both illumination methods laser and LED. Furthermore, a series of sequential velocity fields, produced by the motion of a monofin swimmer, generate a vortex pair with an inverse Karman vortex street which is typically seen in fish and marine mammal locomotion. Consequently, this LED illumination source is shown to provide a sufficient suitable light intensity as well as light quality enabling the measurement of the flow field around swimmers.

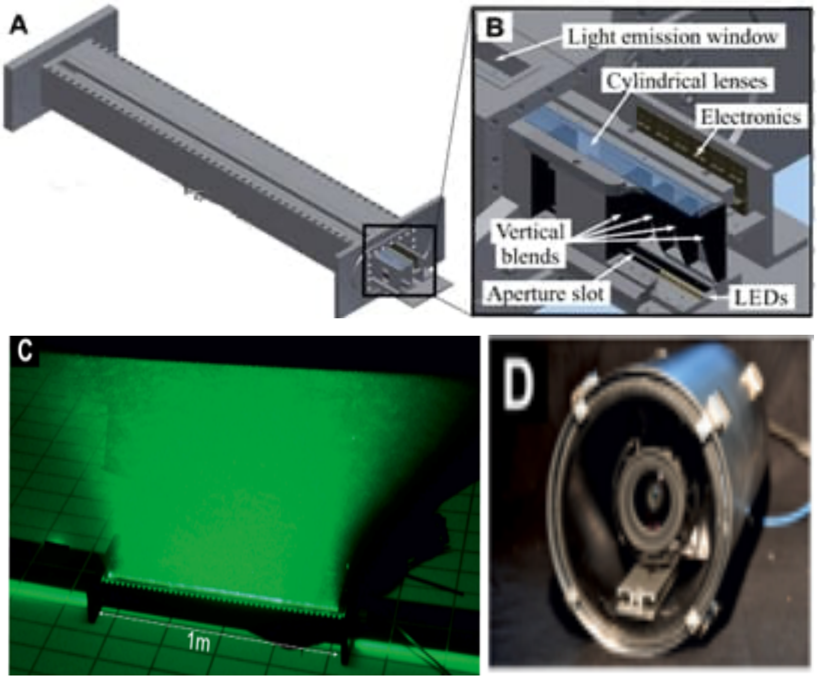

Fig. 2.4 Apparatus of PIV Setup (A) Total view of LED illuminator system and (B) detail-view on its components. The LED light passes through the aperture slot and the cylindrical lenses, before emitting through the window into the water. (C) The LED illuminator system, positioned on the bottom of a swimming pool, creates a homogeneous vertical light sheet of 1 m × 1 m × 20 mm usable for PIV measurements, e.g., on human swimmers. (D) Own underwater housing for the high-speed camera [5]

Bakker et al. [6] showed the development of a high-power pulsed LED line light and its use to apply particle image velocimetry (PIV) during wave impact measurements are described. An electrical circuit that generates high-current pulses is designed and built, which is used to overdrive several commercially available LEDs. The limit for this overdrive-capacity is determined as function of pulse duration for various commercially available LEDs.

Two systems of cylindrical convex lenses are designed to act as a collimator and reduce divergence of the LED bundle and the resulting light sheet properties (maximum light intensity and sheet thickness) are investigated. An array of LEDs of 60 cm length (referred to as the LED line light) is designed and manufactured. For the two lens systems, the LED line light provides proper light sheet conditions to illuminate measurement regions in the order of either 0.3 m × 0.3 m, or 1 m× 1 m, at a sufficiently constant light sheet thickness of 5 mm.

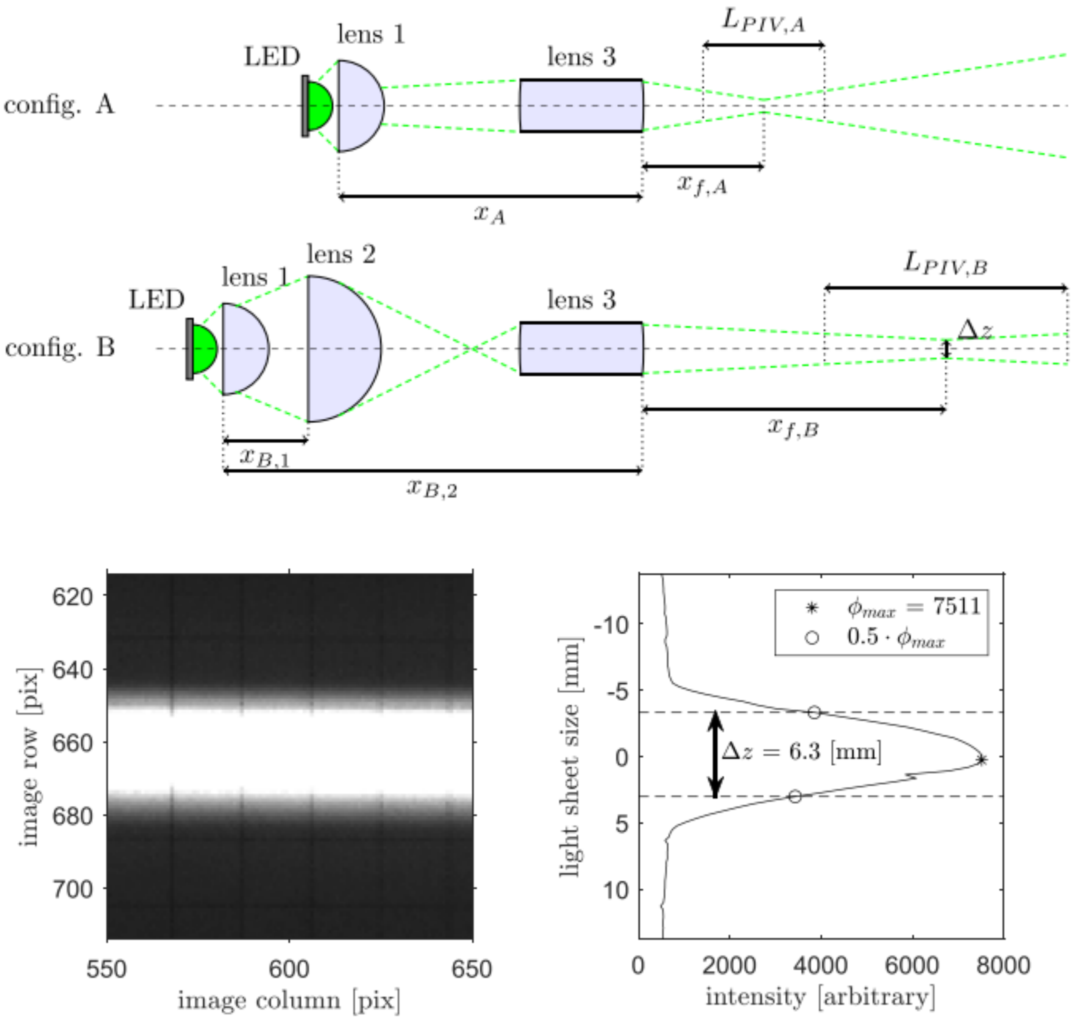

Fig. 2.5 Cylindrical lens apparatus [6]

The application of the LED line light is demonstrated by quantifying the instantaneous flow field of a wave impacting on a blunt object in a wave flume. PIV measurements are conducted at an acquisition rate of 25 frame pairs per second, quantifying maximum flow velocities in the order of 1.0 m s−1 at a LED pulse width of 200 µs. The system, consisting of the LED line light, a CMOS camera and open-source PIV processing software provides the possibility to perform 2D planar PIV measurements for a fraction of the costs of a commercially available laser-based PIV system.

Harshani et al. [7] described that laser systems are expensive, and their usage usually creates specific safety precautions. In this work, they used a low-cost LED based illumination system in conjunction with the refractive index matching method to measure flow velocities in porous media. Hydro jelly beads were used as a transparent porous medium which have the same refractive index as water. The movement of tracer particles which were illuminated by the LED pulse was captured by a high-speed double pulsed camera and the resulting images were processed for receiving the pore-scale fluid velocity. Interstitial velocity vectors averaged over a specified region were presented and compared with the vertical velocity component calculated from the volumetric flow rate. In general, their results demonstrated the usability of LED based PIV system for investigating flow conditions in porous media.

2.3 Attempts towards development of real-time PIV systems:

Kobatake et al. [8] introduced a novel concept of real-time microscopic particle image velocimetry (micro-PIV) for high-speed microchannel flows in a lab-on-a-chip using a frame-straddling high-speed vision system with two camera inputs; it can synchronize two camera inputs with the same view field with a time delay on a sub microsecond time scale. To improve the measurable range of velocity in microchannel flow observation, they proposed a variable-frame-straddling optical flow (VFS-OF) algorithm that can simultaneously estimate the microchannel flow distribution as gradient-based optical flows using frame-straddled images from the two camera inputs; their frame-straddling time is determined by the amplitude of the estimated optical flow to avoid large image displacements between frames that often generate serious errors in optical flow estimation. They built a real-time micro-PIV system by software implementing the VFS-OF algorithm in a high-speed vision system with two frame-straddled cameras; it can execute real time video processing and recording of 512×512-pixel images at 2000 frames per second for the two cameras and control their frame-straddling time from 0 to 0.5 ms with 9.9-ns steps. This micro-PIV system can estimate the velocity distribution of high-speed microchannel flows at 1 m/s or more in real time by controlling the frame-straddling time.

Clusckey and Dantec [9] tells the key point in which systems differ is in the time required from image capture to presentation of the corresponding vector map - the processing time. For practical use this potential time bottleneck can be reduced substantially by very fast processing.

Thus, the focus of this paper was on the camera-illumination control-processing combination for real time PIV measurements. The seedling, laser and illumination light sheet are only briefly mentioned as these are components that are generally available. In this paper, key parameters for successful PIV measurements will be related to the benefits of using a real time processor that allows on-line access to the PIV vector maps. Possibilities for quickly optimizing a set-up were shown. The immediate benefits are shorter experimental time, reduced running costs and the possibility of quickly analyzing long data series for comparison of results with conventional point measurements such as CTA and LDA as weIl as with CFD.

Xing et al. [10] showed that almost all conventional open-loop particle image velocimetry (PIV) methods employ fixed-interval-time optical imaging technology and the time-consuming cross-correlation-based PIV measurement algorithm to calculate the velocity field. In this study, a novel real-time adaptive particle image velocity (RTA-PIV) method is proposed instead of the time-consuming cross-correlation-based PIV measurement algorithm, to accurately measure the instantaneous velocity field of an unsteady flow field. In the proposed closed-loop RTA-PIV method, a new correlation-filter-based PIV measurement algorithm is introduced to calculate the velocity field in real time. Then, a Kalman predictor model is established to predict the velocity of the next time instant, and a suitable interval time can be determined. To adaptively adjust the interval time for capturing two particle images, a new high-speed frame-straddling vision system is developed for the proposed RTA-PIV method. To fully analyze the performance of the RTA-PIV method, they conducted a series of numerical experiments on ground-truth image pairs and on real-world image sequence.

CHAPTER-3
OBJECTIVES, METHODOLOGY AND WORK PLAN

3.1 Objectives

The main objective behind the project undertaken is to develop a low-cost real-time particle image velocimetry system, suitable for use in undergraduate laboratories.

Our aim is to develop a PIV setup to address following issues:

- Generally, PIV uses Lasers, that are too expensive as well as not suitable for exposure to human eye which makes PIV system a bit unapproachable for undergraduates in most colleges. PIV setups are too complex to be handled by undergraduates. Our aim is to design an easy-to-use design for the same.
- We also aim to reduce the time of image processing done in PIV by implementing C++ and GPU code for image processing, to gain a real-time processing of PIV.
- Additionally, we also want to reduce the cost of setup by implementing new ideas like using multiple small Lasers or by using high power LEDs.

3.2 Methodology

We begin with getting insights of Particle Image Velocimetry. How it works? We went through multiple research and conference papers for the same. After realizing the importance of a real time PIV setup, we started to develop a C++ code to make our image processing faster. Moving on to the second aspect of our project, we researched through many papers and proposed a model replacing Laser with high Power LEDs for illumination of seeded particles. It will reduce costs as well as make PIV more user-friendly, reducing the risk of exposure of laser into human eyes.

Then we got proper knowledge of experimental setup of PIV by doing experiments in Lab, and proposed a model which can be used in undergraduate laboratory.

In the last phase we will develop our proposed model and implement GPU on developed image processing code for real time image processing.

3.3 Work Plan

This project is planned to be completed in four phases. The work was distributed in the following manner:

Phase-1:

- Conducted a thorough literature analysis and determined which areas of research require more investigation.
- Got a basic knowledge of how PIV works.
- Started work on development of a code for processing images used for PIV.

Phase-2:

- Went through some research papers to get more insights of PIV and PIV system.
- Worked on C++ Code for analysis of Images and conducted a small experiment for test effectivity of developed code and decided areas of improvements.

Phase-3:

- Worked on other aspects of the project i.e., making a low cost and user-friendly PIV system.
- Developed a working code for image processing for getting real time results.
- Proposed a PIV setup replacing Laser with high power LEDs which will reduce costs as well as make our setup more user friendly.

Phase-4:

- Proposed a PIV setup replacing a single high-power laser with multiple laser pointers which will reduce costs as well as make our setup more user friendly.
- Worked on development of a fully working PIV setup which is proposed above.

CHAPTER-4

DEVELOPMENT OF A LOW-COST ILLUMINATION SYSTEM

Illumination system is one of the major components of a PIV apparatus. Generally, lasers are used to develop a light sheet, which is further used to illuminate the tracer particle. These high-power lasers are not only very costly but also not safe to use. In this chapter, we will see how we can replace these high-power lasers with more user-friendly low power lasers, to increase safety of user of this system and reducing cost as well.

4.1 Traditional PIV Laser Systems

Particle Image Velocimetry (PIV) typically uses high-cost laser systems, such as the pulsed Neodyme-YAG (Nd:YAG) laser. This laser operates at a frequency of 532 nm, with pulse durations of 5 to 10 nanoseconds and a repetition rate of about 10 Hz. The energy output can reach up to 400 millijoules per pulse. These systems consist of two separate laser cavities, with laser beams that superimpose in both the near and far fields to ensure precise illumination of the same area.

The cost of an Nd:YAG laser system can be around $18,000, making it expensive for smaller projects or academic applications. Along with the laser, traditional PIV setups often use CCD (Charge-Coupled Device) sensors for digital image recording. These sensors convert light into electric charges using the photoelectric effect, with individual sensors typically 10x10 micrometres in size. This complex technology further adds to the high cost.

Fig. 4.1 Neodyme-YAG (Nd:YAG) laser [5]

4.2 Cost-Effective Alternative with Multiple Laser Pointers

A low-cost alternative uses multiple small laser pointers to generate the required laser sheets. The CLIMBERTY® Laser Light USB Rechargeable Green Laser Pointer is one such device, emitting green light at 532 nm—the same frequency as Nd:YAG lasers. These laser pointers are compact and made from durable aluminium alloy, with USB rechargeability, making them portable and easy to use. Each unit costs just $5.5, allowing us to use five laser pointers for a total cost of only $27.5. This significant cost reduction is one of the major benefits of this approach. These smaller laser pointers offer several advantages. They are lightweight and portable, allowing for easy transportation and setup. Their USB rechargeability reduces the need for additional power supplies or batteries, making them more convenient and cost-effective. Additionally, the long-range beam (up to 2000 meters) allows for versatility in various applications, such as presentations or stargazing. This compact design makes them an attractive choice for low-cost PIV systems.

Fig. 4.2 Laser Light USB Rechargeable Green Laser Pointer [6]

4.3 Model Overview

In our model, we use five laser pen pointers to create a laser sheet for Particle Image Velocimetry (PIV). These pen pointers emit high-intensity green light at a wavelength of 532 nm. Each pen pointer has a length of 151.15 mm and a diameter of 14.15 mm, offering a compact and portable solution.

4.3.1 Holding Arc Design

To focus the laser beams and create a laser sheet, we designed a holding arc using 3D printing technology. This arc holds the five laser pen pointers in a fixed position, maintaining a precise angle between them to ensure that their beams converge at a designated point. The angle between each pen pointer is set at 18 degrees, allowing the beams to converge in a way that creates a consistent laser sheet. The holding arc is crucial for aligning the laser pens and keeping them stable. The 3D-printed design provides flexibility in positioning and allows for easy assembly and adjustments, which is key for achieving the desired laser sheet effect. With the laser pen pointers secured in the holding arc, we can create a laser sheet that can be used to visualize particles in a fluid flow. This setup produces a laser sheet approximately 20 mm wide, providing adequate coverage for PIV applications. The convergence of the beams allows for focused illumination, which is essential for capturing particle movement during analysis.

Fig. 4.3 Laser Light USB Rechargeable Green Laser Pointer

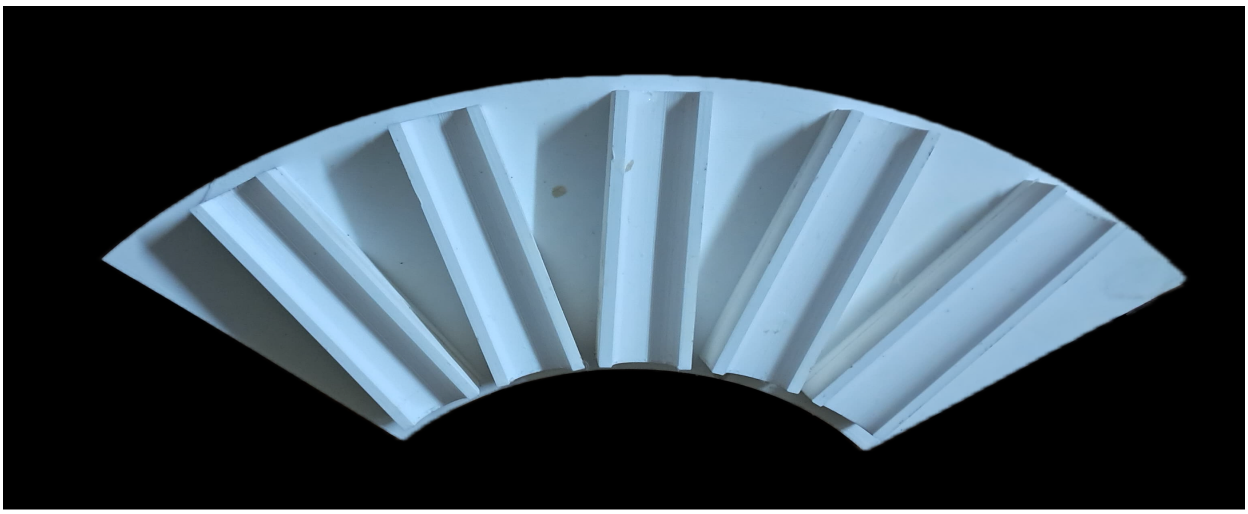

Fig. 4.4 Holding Arc

4.3.2 Laser sheet Generation

Now, lasers can be put in arc holder, with a 20mm cylindrical or glass in at centre of the arc holder i.e. focus point or intersection point of all laser pointers. As a result, we get a laser sheet, which is used to illuminate tracer particles in flow and further can be used as illuminating system in PIV.

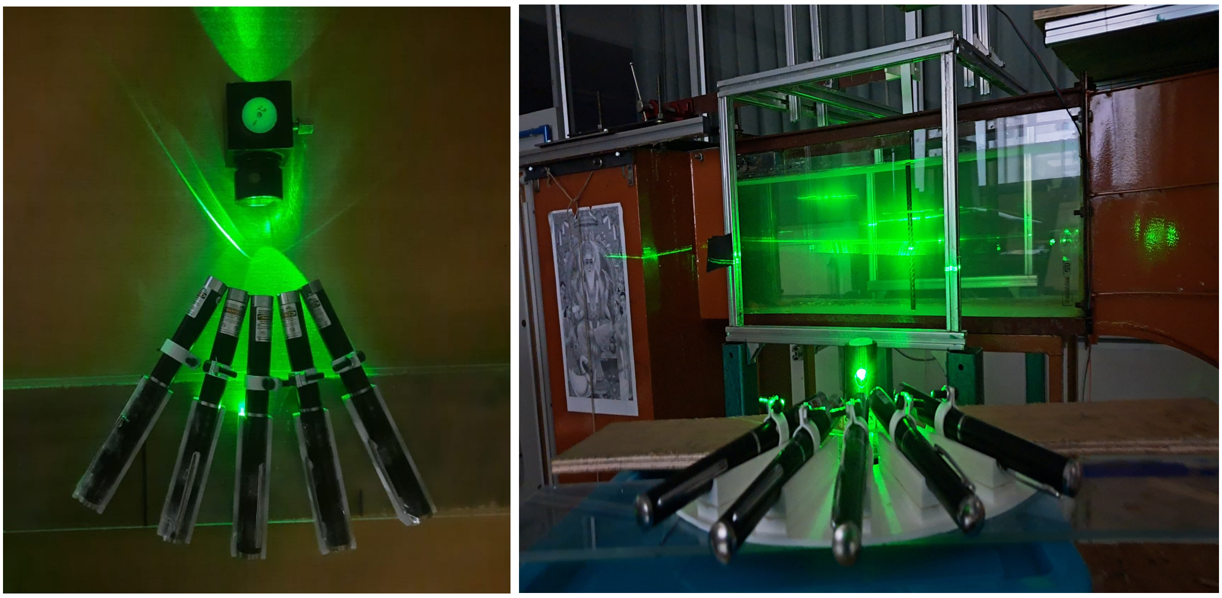

Fig. 4.5 Final apparatus with multiple small laser pointers

This model with a suitable setup of lens, can be used in the laboratory for beginners. This will not only increase the safety but also minimised the cost of the system.

CHAPTER – 5
COMPARISION, ADVANTAGES, LIMITATIONS AND COST REDUCTION

5.1 Comparison of Laser Systems

Traditional Particle Image Velocimetry (PIV) systems often rely on high-cost lasers such as the pulsed Neodyme-YAG (Nd:YAG) laser. These systems are known for their high energy output, stability, and precision. However, they come with significant costs, both in terms of equipment and maintenance. In contrast, the low-cost setup that uses five laser pen pointers and a 3D-printed holding arc is designed to be more budget-friendly while still providing a functional laser sheet for PIV.

Nd:YAG lasers are capable of pulse durations of 5 to 10 nanoseconds, with a repetition rate of about 10 Hz, delivering energy levels up to 400 millijoules per pulse. In contrast, the laser pen pointer setup uses lower-energy sources, focusing on creating a stable laser sheet rather than high-energy pulses. This makes the setup more suitable for smaller-scale applications where budget constraints are the concerns.

5.2 Advantages of the Low-Cost Laser Setup

The primary advantage of the low-cost laser setup is its affordability. Using laser pen pointers significantly reduces the cost compared to traditional systems. Each pen pointer costs only $5.5, and with five pointers used in the setup, the total cost for the laser components is just $27.5. This is a dramatic reduction compared to traditional PIV laser systems that can cost up to $18,000.

Another advantage is portability and ease of setup. The laser pen pointers are compact and lightweight, making them easy to transport and set up in various environments. Additionally, the 3D-printed holding arc provides flexibility in design, allowing for customization and adjustments as needed.

5.3 Limitations of the Low-Cost Laser Setup

Despite its advantages, the low-cost laser setup has some limitations. The energy output and beam stability of the laser pen pointers may not match those of traditional Nd:YAG lasers, potentially affecting the accuracy of PIV results. Misalignment of the laser beams due to the holding arc or other factors can also lead to inconsistent laser sheets, impacting the quality of the PIV analysis.

Safety is another consideration, as laser pen pointers can pose risks if not handled properly. Users must take precautions to avoid eye injuries and ensure the setup is kept away from children.

5.4 Cost Comparison and Cost Reduction Percentage

The cost comparison between the traditional Nd:YAG laser system and the low-cost laser pen pointer setup reveals a significant difference. Traditional PIV systems can cost up to $18,000, primarily due to the high expense of the Nd:YAG lasers and associated components. In contrast, the total cost for the laser pen pointer setup, including five laser pointers and the 3D-printed holding arc, is just $27.5.

$$\text{Cost Reduction Percentage} = \frac{(OC-NC)}{OC} * 100 \;\ldots\ldots\ldots\ldots\ldots\ldots\; (1)$$

Substituting the values, we get:

$$\text{Cost Reduction Percentage} = \frac{(18000-27.5)}{18000} * 100 \;\sim 99.85\%$$

This calculation indicates that the cost is reduced by approximately 99.85% when using the low-cost laser pen pointer setup compared to a traditional Nd:YAG laser system.

5.5 Results

After making a proper setup we get following results with our multiple laser illumination system.

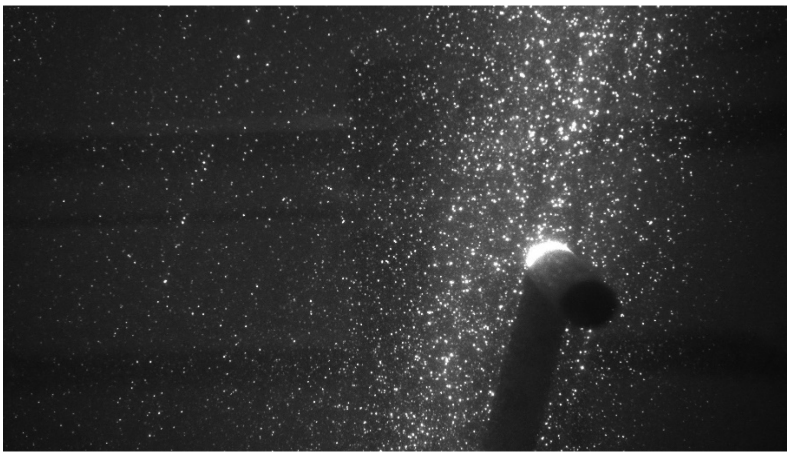

Fig. 5.1 Illuminated tracer particles by multiple laser pointers setup.

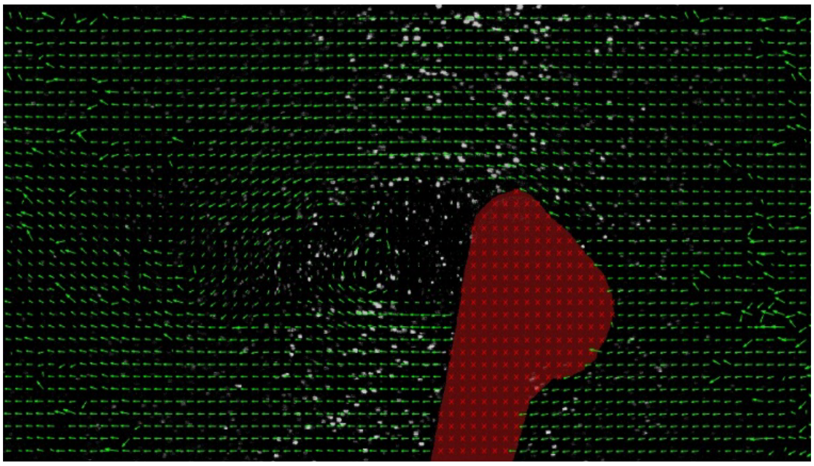

Fig. 5.2 Displacement vector as a result from above sample

Although we can perform PIV and can get a basic knowledge of how PIV works with this model, this cannot be used as a professional and for deep research purpose. But as our aim was to develop a system for beginners, this system can serve our need of same.

5.6 Limitations

As we mentioned, we cannot use this system for a deep research purpose, following are the reasons and respective solutions for generated errors-

1. As we are using a battery source, the power of our system is not constant. Power will reduce after every use of laser pointer. We can use DC source to make an approximate constant power source.
2. Our setup is 3D printed and may have some alignments issues. A small change in angle can lead our laser to not converge at center. Which will lead to formation of multiple planes of sheet.
3. We need to converge each and every laser pointer to centre approximately, a small change can lead to generation of multiple sheets or can also increase the thickness of sheet.
4. We need to also make an account of thickness of sheet. If our sheet is too thick than it may cause error in results.
5. We should also update our setup so that our all elements of setup like lasers, lens and holding arc can be put in a single box or container. It will not make our setup user friendly but also increase accuracy by reducing chances of misalignments.

By working on these above points, we can make our setup more accurate and effective for research purpose.

CHAPTER-6
CONCLUSION AND FUTURE SCOPES

In the present report, we have seen the various work done in the direction of development of real-time cost-effective Particle Image Velocimetry making it a more approachable and user friendly. We presented our understanding which we got in this report.

Along with this we focused on understanding image processing in PIV continuing our last phase work. We get a proper insight into the history, development and working of Cross-Correlation technique concluded in last phase work.

In this phase we proposed a cost effective and user-friendly model which can be used in undergraduate level laboratory for research. We have worked in the direction of replacement of Laser illumination method with some other illumination techniques with a setup consisting multiple laser pointers instead of a single high-power laser. Although some work is already done in this field, it is done by sacrificing result quality. We tried to focus on getting better results along with reducing the cost of the setup.

At last, we made our proposed model, which we developed in chapter 4, done a cost analysis and largely reduced the cost.

In the future, we can work on the image processing unit and try to reduce costs by adapting some more optimal techniques.

REFERENCES

[1] Raffel, Markus, Christian E. Willert, Fulvio Scarano, Christian J. Kähler, Steve T. Wereley, and Jürgen Kompenhans. “Particle image velocimetry: a practical guide”. *springer*, 2018.

[2] Bhakta, Rajkumar. “Development of a Low-Cost, Multiple-Diode, Continuous Laser for PIV Applications”. *New Mexico Institute of Mining and Technology*, 2018.

[3] Ring, Brock Philip, and Evan C. Lemley. "Design and implementation of a low-cost particle image velocimetry system for undergraduate research and education." In *2014 ASEE Annual Conference & Exposition*, pp. 24-365. 2014.

[4] Budd, Aaron, and Jason Howison. "A low-cost PIV system for undergraduate fluids laboratories." In *2018 ASEE Annual Conference & Exposition*. 2018.

[5] Hochstein, Stefan, Anvar Jakupov, Jens-Uwe Schmollack, Daniel Sporer, Veit Wank, and Reinhard Blickhan. "An alternative illumination source based on LEDs for PIV measurements on human swimmers—A feasibility study." *Flow Measurement and Instrumentation* 88 (2022): 102251.

[6] Bakker, Wout, Bas Hofland, E. De Almeida, Gosse Oldenziel, and E. F. J. Overmars. "Pulsed LED line light for large-scale PIV—development and use in wave load measurements." *Measurement Science and Technology* 32, no. 11 (2021): 115205.

[7] Harshani, H. M. D., S. A. Galindo-Torres, and A. Scheuermann. "Particle Image Velocimetry with high power Light Emitting Diodes for flow through porous medium." *WIT Transactions on Engineering Sciences* 89 (2015): 501-511.

[8] Kobatake, Motofumi, Takeshi Takaki, and Idaku Ishii. "A real-time micro-PIV system using frame-straddling high-speed vision." In *2012 IEEE International Conference on Robotics and Automation*, pp. 397-402. IEEE, 2012.

[9] McCluskey, D. R., and E. Hayes. "Real-Time Signal Processing in Particle Image Velocimetry: The importance of real-time image processing in optimizing data collection and analysis in Particle Image Velocimetry." In *Three-Dimensional Velocity and Vorticity Measuring and Image Analysis Techniques: Lecture Notes from the Short Course held in Zürich, Switzerland, 3–6 September 1996*, pp. 93-112. Dordrecht: Springer Netherlands, 1996.

[10] Ouyang, ZhenXing, Hua Yang, Jin Lu, YongAn Huang, and ZhouPing Yin. "Real-time adaptive particle image velocimetry for accurate unsteady flow field measurements." *Science China Technological Sciences* 65, no. 9 (2022): 2143-2155.

WEB RESOURCES

[1] https://circuitglobe.com/wp-content/uploads/2018/03/circuit-aneometer.jpg

[2] https://borgoltz.aoe.vt.edu/aoe3054/manual/expt4/

[3] https://www.academia.edu/96097895/A_Low_Cost_Particle_Image_Velocimetry

[4] instrumentationtools.com/wp-content/uploads/2018/03/Laser-Doppler-anemometer.jpg

[5] https://www.cnioptics.com/dp-green-laser.html

[5] https://www.cnioptics.com/dp-green-laser.html

[6] https://images.app.goo.gl/TvhezzbKd7X4Y8EeA