ECE 445

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

Particle Image Velocimetry

Team #8

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1 Introduction

1.1 Problem

Understanding how fluids move is crucial for many scientific and engineering applications. Nowadays, Particle Image Velocimetry (PIV) has evolved to be the dominant method for velocimetry in experimental fluid mechanics and has contributed to many advances in our understanding of turbulent and complex flows. However, we found out that the PIV equipment for experimental use was not straightforward enough for lower-grade students to understand the basic principle, also it had some restrictions on the environment and a relatively high cost. As a result, we plan to design a low-cost, easy-maintaining, and portable device that can demonstrate how PIV works in a simple way without many restrictions on the environment. We also add some interactive functions so it can give a deep impression on students and raise their interest in fluid dynamic study.

1.2 Solution

We propose to develop a device that can detect the state of particle motion in a flowing channel and present it in an intuitive way. Our design includes some distinct subsystems to realize relatively accurate and real-time measurements. Within the design, the Flowing Channel Subsystem ensures continuous air circulation through a sophisticated channel system driven by a blower and we plan to use small and light particles like styrofoam to be the tracer particles. The Laser and Optical Subsystem incorporates an adjustable laser source and optical components, such as lenses and mirrors, to illuminate a certain area in the flowing channel, in order to gain clear images of particles. The Image Acquisition Subsystem, equipped with a digital camera, captures and aligns particle images, forwarding them to an Image Processing System for precise velocity calculations, data analysis, and data visualization. The User Interface and Data Visualization Subsystem offers a user-friendly platform with a display for real-time fluid images and velocity field visualizations, enabling efficient monitoring and analysis of fluid dynamics. This holistic solution caters to applications demanding accurate and timely fluid velocity information without duplicating details from the specified components. Our PIV device also can provide some fun parts to help them understand how it works and raise their interest in fluid dynamics.

1.3 Visual Aid

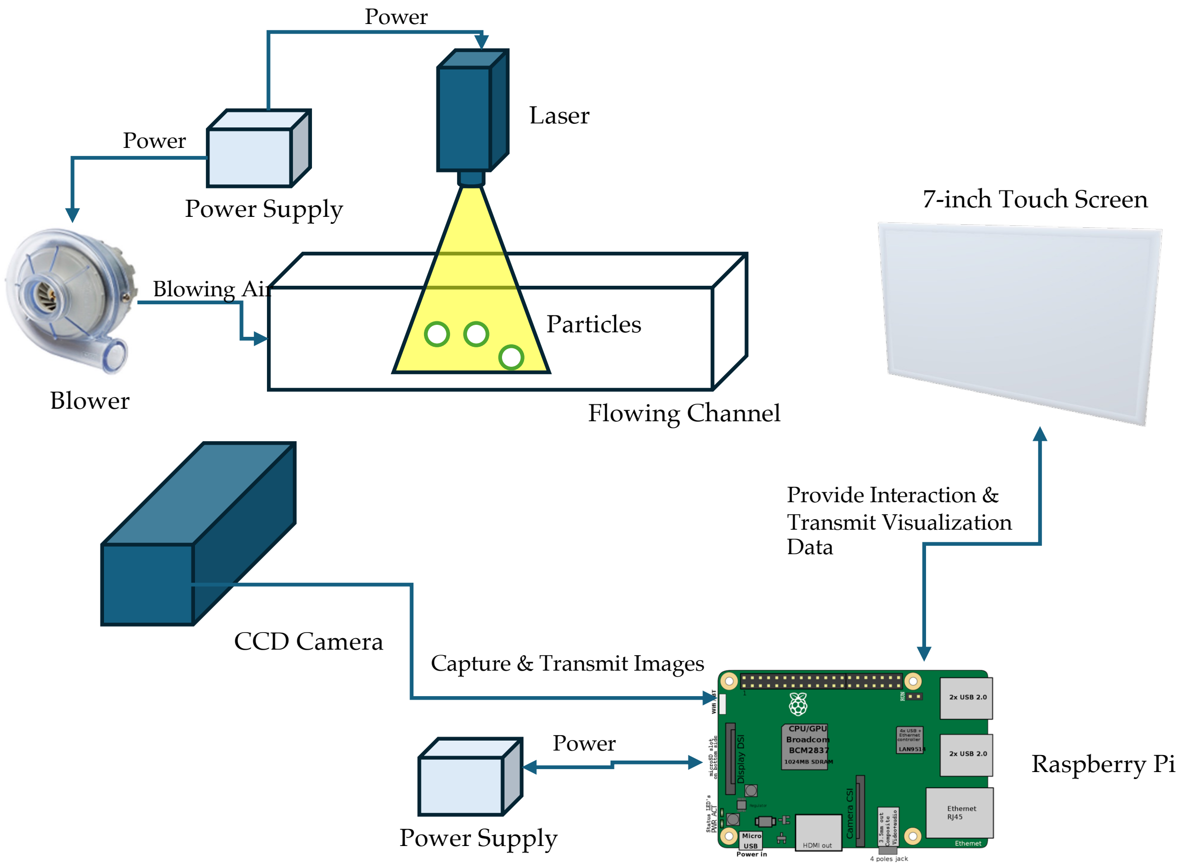

Figure 1: Visual Aid

1.4 High-level requirements list

- The system needs to be able to estimate the velocity magnitude and direction of the particles when estimating the particles, and we would like the velocity magnitude to be within 20% error and the angular deviation to be within 20 degrees when comparing the results of our measurements with the professional results.
- The system should offer an interactive experience with a user-friendly interface that includes real-time visualizations, e.g., particle images, particle velocities, and calculated flow rate of fluids.
- The instructor can control the device manually and demonstrate how the PIV device works directly or choose to control the device like how the users do. Under the instruction and supervision, students should be able to control the PIV demonstration, e.g., toggling on or off the measurement and changing the flow rate of fluids, with a real-time graphical user interface (GUI).

2 Design

2.1 Block Diagram

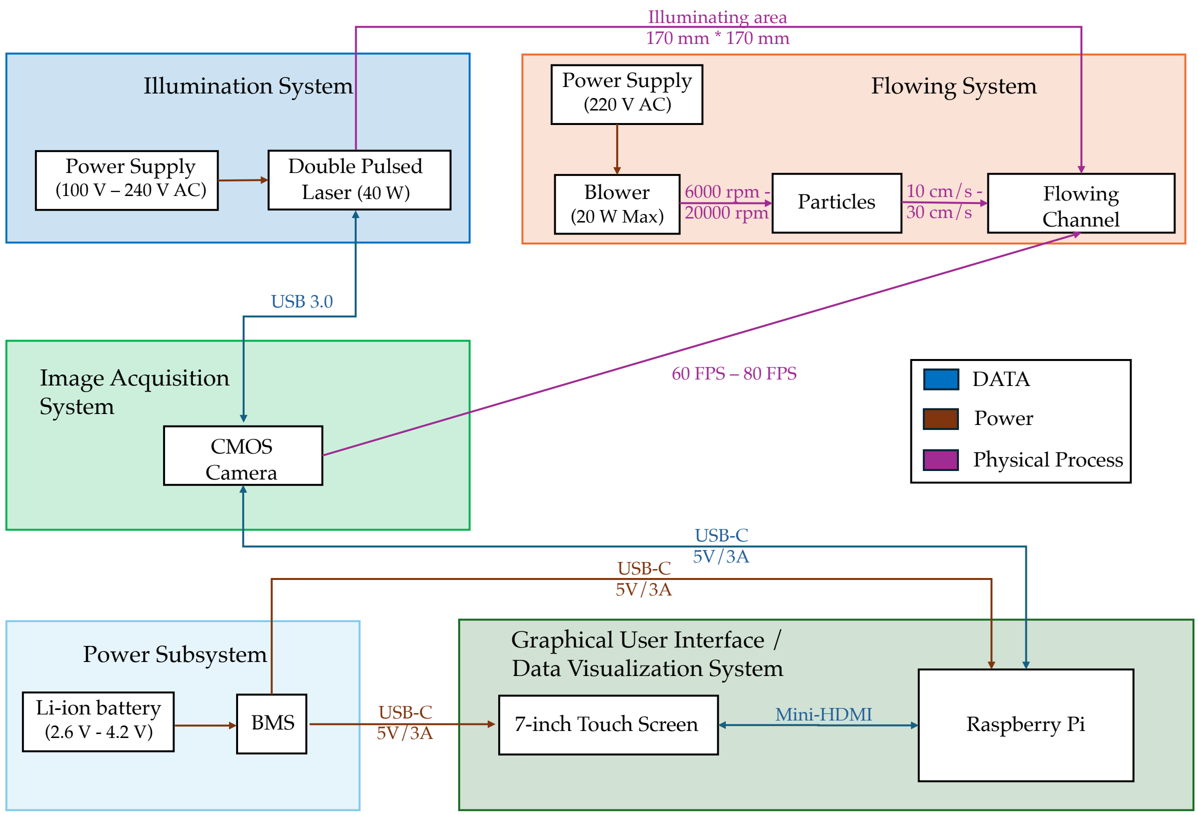

Figure 2: Block Diagram

2.2 Subsystem Overview

- Flowing System: This system contains an acrylic-build flowing channel, a power supply, a blower, and the particles. The power supply provides 220 V AC voltage so that the blower can rotate at 6000 rpm - 20000 rpm to make the particles flow at an estimated speed of 10 cm/s - 30 cm/s.
- Illumination system: The illumination system consists of a laser source with adjustable position and a complete set of devices for generating a clear spot and image. Adjustments are made via computerized feedback with the Image Acquisition System.
- Image Acquisition System: The camera captures an image of the particles in the fluid, calculates the velocity of the particles does the raw data analysis. It is connected to the Illumination System via a Raspberry Pi and feeds back to each other.

- Interactive User Interface: A 7-inch touch screen driven by the Raspberry Pi displays a GUI, which allows instructors and students to control various aspects of the PIV system, view real-time data, and adjust settings as needed.
- Data Visualization System: Data visualization software executing on the Raspberry Pi enables users to visualize the velocity of particles within the fluid in real time, providing an intuitive and interactive way to understand complex fluid dynamics.

2.3 Subsystem Requirements

2.3.1 Flowing System

- Transparent container that allows fluid to flow through. The container we intend to use is a hollow acrylic cylinder with 15 cm in diameter and 1 m long.
  There is a manually operated 20 W Max blower that ensures that the air and particles can circulate through the flowing channel. We can measure and control the flow rate of the air. We put the particles in the flowing channel before we turn on the blower. The Flowing System must ensure that a relatively closed environment that other air disturbances in the environment will not affect the flow. In the system, the particles can flow at a speed of 10 cm/s - 30 cm/s.
  For the particle selection, Jingsong[1] has provided some standards: particles should have a close to sphere shape in order to give a homogeneous image at any orientation. Particles should also be distributed evenly in the field so that the same accuracy can be obtained throughout the whole image area. This also guarantees that the two correlated images will not see a dramatic change in particle density. Such a sudden change in image density can introduce a large number of unmatched image pairs, and hence, introduce measurement ”noise” to the result. So the shape should be as round as possible and the size distribution should be as uniform as possible and there should be a sufficiently high light scattering efficiency.
  Also, the tracer particles can should have a volume fraction of less than 10^6[2] in order to eliminate the effect it would bring to the flow.

2.3.2 Illumination System

- A laser source that provides a laser beam for illuminating particles in the fluid and ensures that the laser source is position adjustable. And contains an optical system including lenses, mirrors, and filters for creating a clear spot and image. The double-pulsed laser needs a power of 40 W and the power supply for the illumination system should be a 100 V - 240 V AC.

2.3.3 Illumination System

- A camera is used to capture images of the particles in the fluid, sending the captured pictures to an image processing system, which, is used to calculate the particle velocity. At the same time the camera makes sure to align the particles in the fluid channel. The camera should have high spatial resolution, high sensitivity, short and accurate inter-frame time, and sometimes high frame rates. The frame rate of the Camera should be between 60 fps to 80 fps. The camera needs 5 V / 3 A power input via USB-C cable and transmit information via USB 3.0 cable.

2.3.4 Interactive User Interface

- The GUI should ensure that users can find functions within 3 clicks or less on a 7-inch touch screen. It should respond to user inputs and reflect changes in the system within 100 ms. The GUI should load within 10 seconds upon startup and respond to user interactions within 500 ms. The GUI should provide real-time status feedback of the mechanical components so users can verify that commands have been executed correctly. The GUI should ensure that only authorized users can send commands to the system.

2.3.5 Data Visualization System

- The system should be able to update visualizations to reflect real-time data with a maximum delay of 200 ms. The system must enable users with little technical background to interpret data correctly, providing contextual help where necessary.

2.4 Tolerance Analysis

The velocity is calculated by the following formula:

$$V = \frac{\Delta X}{\Delta t}$$
$$\Delta X = \frac{D_p A}{R}$$

where Δt is the time interval between successive images. D_p is the average displacement of particles between successive images, measured in pixels; A is the size of the area being imaged; R is the resolution of the digital camera, measured in pixels.

The main error may come from the following sources: 1. Error in Δt. We require the digital camera to take successive photos in a short time. If it happens to have a delay in taking photos, the actual Δt will be different from the expected one. 2. Error in ΔX. This error includes errors in measuring the displacement between the particles (D_p) and the error in measuring the size of the imaged area (A).

To achieve our expected precision of the measurements (within 20% error), we need to ensure:

1. The inter-frame time accuracy of the camera. Assume the displacement measurement is accurate and we use a camera of 60 fps, namely $\Delta t = \frac{1}{60} \approx 0.01667$s. The tolerated inter-frame time interval is between $\frac{1}{1 \pm 0.2}\Delta t \approx 0.01389$ s $-$ 0.02083 s.

2. The accuracy of the displacement measurement. Assume we use a camera of 60 fps and its inter-frame time is exactly 0.01667 s. We consider two cases here, the minimal estimated velocity 10 cm/s and the maximum estimated velocity 30 cm/s. When the velocity is 10 cm/s, we need to ensure $\Delta X < 0.2 * V * \Delta t = 0.0333$ cm in two successive photos. Similarly, when the velocity is 30 cm/s, we need to ensure $\Delta X < 0.1$ cm.

3 Ethics and Safety

In this project, we consider following ethics and safety concerns:

3.1 Ethics

- Privacy. The IEEE and ACM[3] codes also require engineers to respect the public's privacy. Since our design includes a voice control system, we need to ensure that the information we obtain will not be disclosed for other uses.
- Educational impact. Since our project will be applied to education, especially to demonstrate PIV to children, we need to ensure the system has a positive educational impact, reducing confusion and avoiding any harm to the users. For this reason, we plan to create materials that explain the principles of the PIV measurement and operation mannual of the control system in an age-appropriate manner.

3.2 Safety

The IEEE[4] code emphasizes the importance of prioritizing safety and health in engineering project, "to hold paramount the safety, health, and welfare of the public." This is strongly relevant to the most of the system in our design.

- Laser Safety. Safety notes in the LD-PS/5[5] states that The laser must only be used when integrated into a system that does not allow laser radiation to exit the system. Any eye and skin exposure to the light must be strictly prevented. Never operate the device without the cylindrical divergent lens. Never point the laser beam at humans animals or flammable materials. Fire, serious injury, or death might result from this action. Never adjust the laser while it is turned on. Safety goggles are suggested for use while operating.
- PM Safety. When the blower is blowing air, it can carry some particulate matter. The United States Environmental Protection Agency[6] declares that Exposure to such particles can affect both your lungs and your heart. Numerous scientific studies have linked particle pollution exposure to a variety of problems, including: premature death in people with heart or lung disease; nonfatal heart attacks; irregular heartbeat; aggravated asthma; decreased lung function; increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing. People with heart or lung diseases, children, and older adults are the most likely to be affected by particle pollution exposure.
- Blower Safety. The operating blower can work at a speed of 20000 RPM. The OSHA training[7] states that using a compressed air blower presents potential hazards that can do serious harm to the user, as well as to other people working in close proximity. Flying chips, dust, and particles can be sent flying through the air at a high rate of speed and strike someone, causing cuts and abrasions to their skin or an eye. And if a compressed air blower is activated when placed directly against or near the skin or other body parts of a person, the high-pressure stream of air can actually

pierce the person’s skin, inject air or chemicals into their bloodstream, rupture an eardrum, or permanently damage an eyeball.

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