A Low-Cost, Portable, Smartphone Schlieren Imaging System

Abstract

We introduce a smartphone schlieren imaging system for application in the undergraduate fluid mechanics laboratory. This system provides a low-cost schlieren imaging alternative for project-based learning and is based on a single-mirror setup, with the smartphone flash serving as the light source and the smartphone camera as the detector. Adjustable mounts for the smartphone and mirror are 3D printed and secured to a common base, allowing for the apparatus to be relocated as a single, portable system. Situations involving refractive index variations, such as compressible gas flows and thermal convection flows, can then be recorded by the camera as images. Construction of the smartphone schlieren imaging system is straightforward and accessible to lab groups operating with a very limited budget, with all parts being 3D printable or otherwise commercially available.

Introduction

At Bethel University, fluid mechanics is included in the physics and engineering curriculum as a junior-level course and a corequisite laboratory. The lab component is integrated in the course in the form of several lab activities and a more extensive open-ended project. The lab seeks to merge ongoing research and academic studies in a productive and engaging experience. Lab activities are enhanced by proficiencies gained by students in previous coursework, such as electronics and physical optics. Moreover, projects allow students to explore a particular fluids-related application with a team, while drawing on the diverse skill sets and interests of the individual team members. Over the past decade, numerous student projects have utilized advanced optical techniques to study a variety of phenomena involving compressible flows, shock waves, and thermal convection flows [1, 2, 3, 4]. Most of these studies have been confined to the fluid mechanics laboratory and have relied on expensive equipment including research-grade optics tables, high-end optics and digital video cameras. In this paper we describe a smartphone schlieren imaging system that is accessible to lab groups operating with limited funding.

Schlieren imaging is a popular flow visualization technique because despite its straightforward setup and reliance on very simple geometrical optics principles, it is a powerful method for capturing high-quality images of what would otherwise be invisible flow phenomena [5, 6, 7]. There are many different optical setups used in schlieren imaging, but each is based on the bending of light through a transparent material with refractive index variations, such as those associated with the density fields of compressible and thermal convection flows. These density variations are invisible to the naked human eye, but can be effectively detected and imaged with schlieren optics. The ability to see the invisible nature of flows is valuable in an introductory fluid mechanics course and can serve to enhance student learning, establish intuition, and stimulate an excitement for the subject of fluid mechanics.

Perhaps the most straightforward and intuitive setup for schlieren imaging is the single-mirror system, shown in Figure 1 below [5]. In this setup, a small light source is positioned near the center of curvature of a concave mirror, which focuses the light at a position closely adjacent to the light source. A knife-edge is precisely positioned at the focal point to block approximately half of the light and a camera is positioned beyond the focused light, aimed at the mirror. The fluid flow test region is positioned just in front of the mirror. Density variations in the flow cause the rays of light to arrive at the knife edge at slightly displaced positions. The distortion of the focused light allows some previously blocked rays of light to pass by the knife edge and some previously unblocked rays to be obstructed by the knife edge. The result is a "schlieren image" depicting the density variations in the flow. It should be noted that, with the single-mirror setup, rays of light take a slightly different path through the test region while traveling from the light source to the mirror compared to traveling from the mirror to the camera. Thus, spacing between the light source and knife edge should be minimized to avoid a noticeable double image.

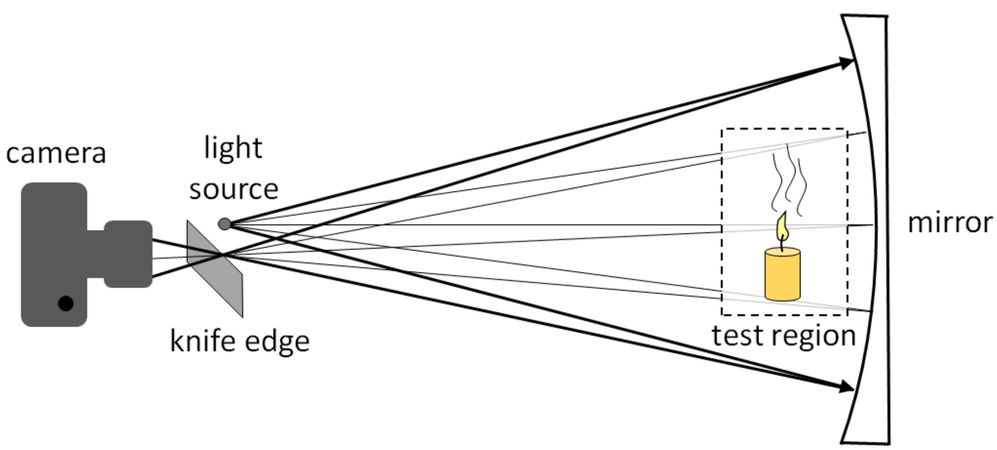

Figure 1: Single mirror schlieren setup.

Smartphone schlieren imaging system

An ordinary smartphone offers a low-cost, portable option for schlieren imaging and project-based learning [8, 9, 10]. By design, a smartphone is well-suited for a single-mirror schlieren setup, with the flash serving as the light source and the smartphone camera lens as the detector.

A smartphone schlieren system is initially set up on an optical table for a proof of concept test as shown Figure 2. The camera flash is positioned near the center of curvature of a concave mirror, which is twice the focal length of the mirror. A piece of black electrical tape, with a small pinhole, is placed over the flash so that it acts as a point source. A second piece of tape covers one half of the camera lens and acts as the knife edge. Finally, the orientation of the mirror is adjusted such that the focused light from the flash is centered on the "knife edge." A lit candle is positioned in front of the mirror to test the setup. As seen in Figure 2, the schlieren image displayed by the camera clearly depicts the otherwise invisible plume of hot air rising from the candle, with the candle and spherical mirror displayed in the background.

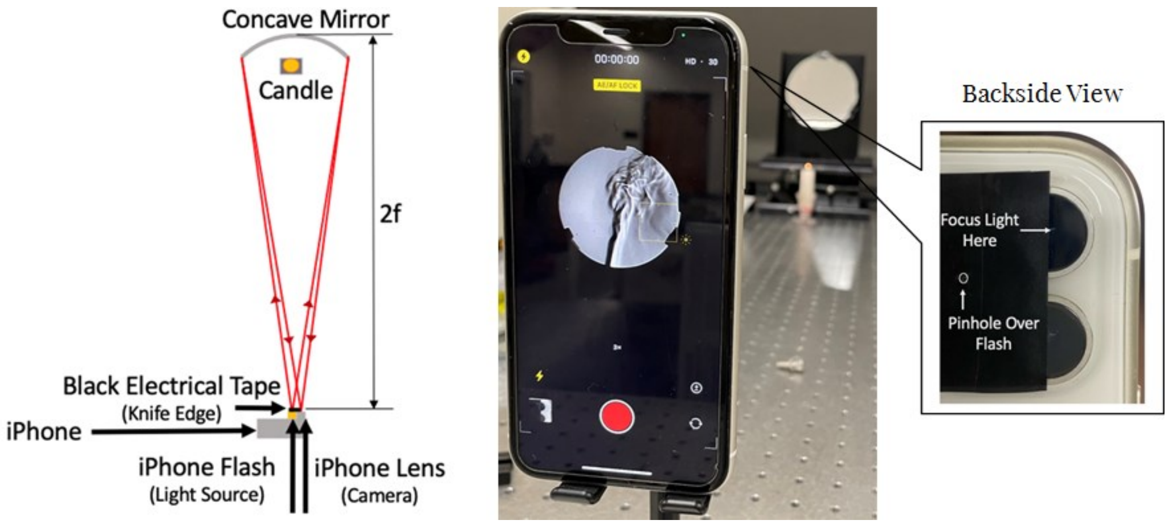

Figure 2: Proof of concept with an iPhone 11 (smartphone schlieren setup on optical table).

Following the proof of concept demonstration, a prototype for a portable smartphone schlieren imaging system is designed and constructed. The system does not require an optical table or sophisticated lab equipment. Instead, construction is straightforward, with all parts being 3D printable or otherwise commercially available. The complete system (with the exception of the smartphone) can be constructed for under $100, excluding the materials for 3D printing, which vary. The prototype has a few main components including an adjustable mirror mount, a phone mount with three translational degrees of freedom, and a base that connects the mirror and phone mounts.

A 150-mm diameter, 150-mm focal length mirror was selected for the prototype system. Rather than using high-grade optics, the mirror is an inexpensive bathroom vanity mirror costing less than $20, sold by Eisco Labs (Part Number PH0520O). The mirror is secured in a 3D printed mount as shown in Figure 3. Dimensions are set to fit the 150-mm-diameter mirror, but can be customized to fit another mirror without requiring additional changes to the smartphone schlieren system. The mirror mount is secured to a plywood board at three points using adjustable screws and compression springs, which allows for fine adjustments in the tilt of the mirror to position the focused light on the knife edge.

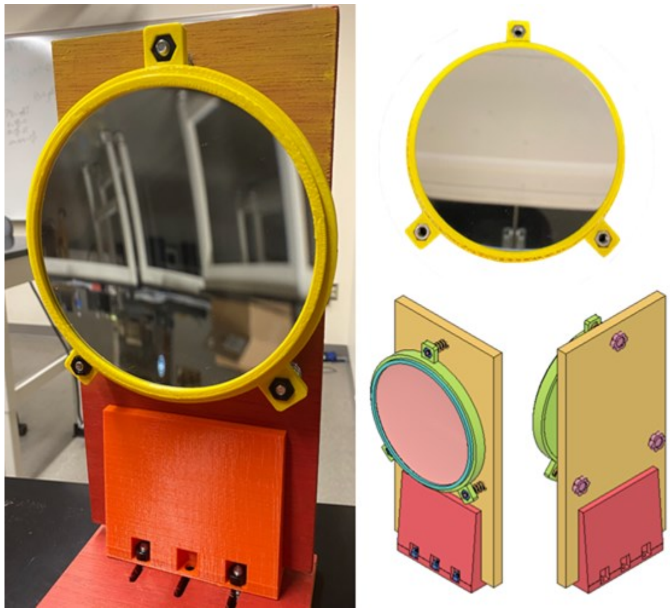

Figure 3: Smartphone schlieren prototype mirror mount.

A 3D printed kinematics mount is constructed to secure and position the smartphone as shown in Figure 4 [11]. The mount allows for adjustments in three translational degrees of freedom and accommodates most smartphone models. Fine adjustments are made with knobs for left/right and forward/backward adjustments. Coarse vertical adjustments are made by sliding the phone up or down within the clamp. The knobs used to adjust the tilt of the mirror also allow for fine vertical adjustments.

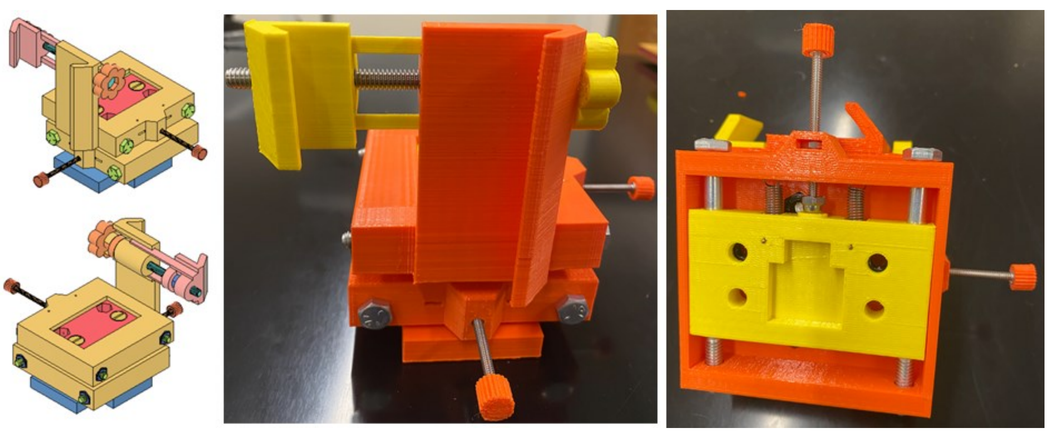

Figure 4: Smartphone schlieren prototype phone mount.

The mirror and phone mounts are secured and coupled with a plywood base (see Figure 5). The base dimensions (150 mm × 300 mm) are to accommodate the 150-mm focal length mirror, which has a radius of curvature of 300 mm. Thus, the 300-mm length of the base allows the camera flash to be positioned at the center of curvature of the mirror. The mirror and phone mounts are secured in slots that were machined in the plywood base. The slots allow for adjustable positioning of the phone and mirror to accommodate alignment of the schlieren system with other smartphones and with mirrors of slightly differing focal lengths.

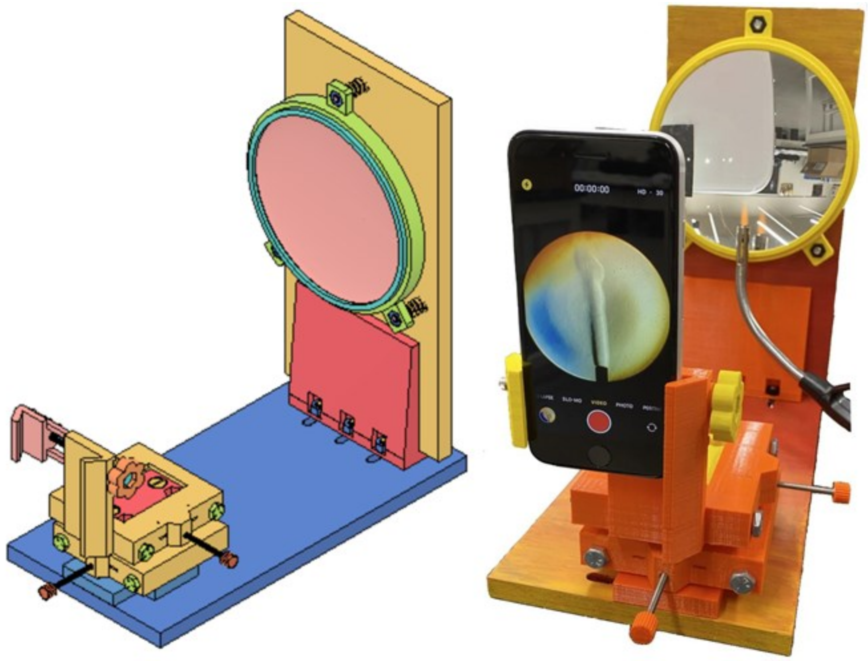

Figure 5: Smartphone schlieren prototype; CAD drawing (left), constructed prototype (right).

The sample schlieren image displayed in Figure 5 (right side) portrays the hot flow from a butane lighter. Producing images with the assembled smartphone schlieren system is quite intuitive once the general concept of schlieren imaging is understood. After placing black electrical tape with a pinhole over the flash and another piece over the camera lens to act as the knife edge, the smartphone is secured in the phone mount. The camera is positioned such that the flash is roughly at the center of curvature of the mirror. Next, the flash is turned on and the system is aligned by focusing the reflected light from the flash on the knife edge and centering it on the circular camera lens. In order to achieve this, the tilt of the mirror is first adjusted to bring the focused light onto the knife edge. Then, the fine forward/backward adjustment is used to bring the light in sharp focus and the fine left/right adjustment is used to precisely center the focused light on the camera lens, such that half of the light is blocked by the knife edge and half is entering the lens. A video tutorial of the alignment process is posted on YouTube (https://youtu.be/fPnb1sB48YA) [12].

Results

Sample images of fluid flows captured with the smartphone schlieren system are displayed in Figure 6. The top three images are still shots of flow from a compressed gas duster can (left), a burning resistor (middle), and thermal convection from a hot nichrome coil (right). It is worth noting that the single-mirror setup images the actual object producing the flow, such as the resistor or coil, along with the superimposed schlieren image. The bottom four images are a sequence of consecutive images of the flow initiating from a compressed gas can and recorded at 240 frames/second with an iPhone 11.

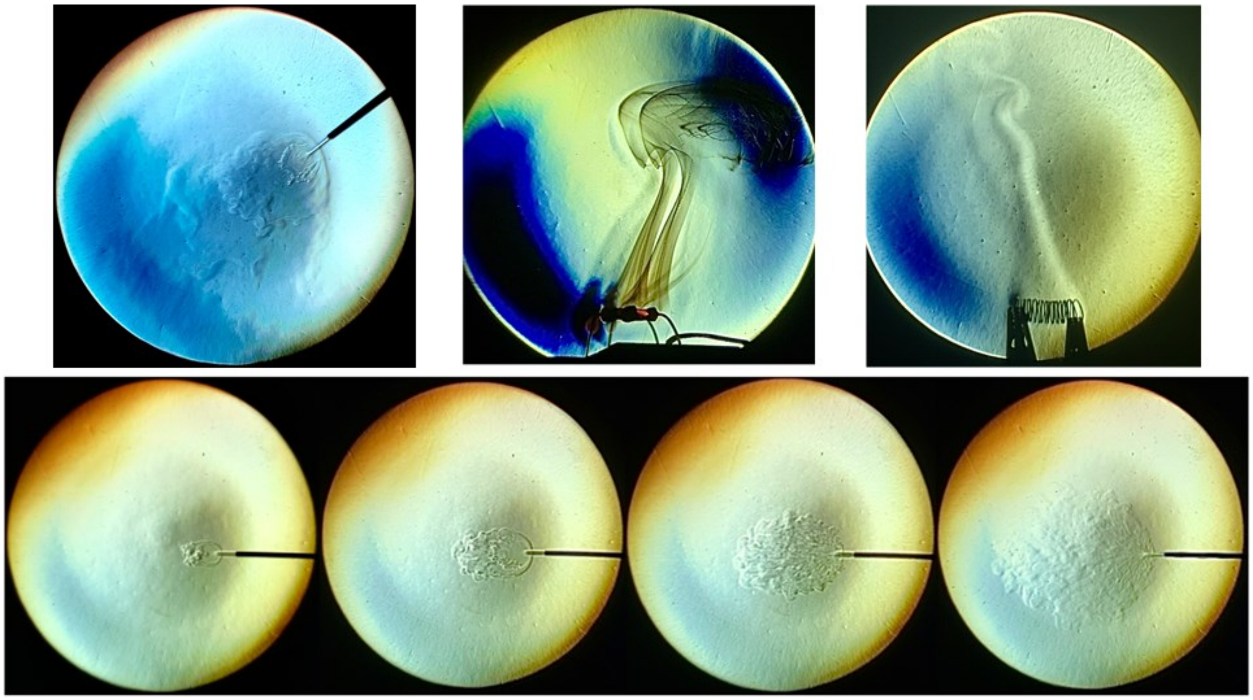

Figure 6: Sample images; Top row (jet from compressed gas duster can,
burning resistor, thermal convection from hot nichrome coil),
Bottom row (sequence at 240 frames/second of flow initiating from an air duster can).

Conclusion

In this paper we described a portable smartphone schlieren imaging system that is available to lab groups operating with a very limited budget. All parts are 3D printable or otherwise commercially available and the complete system (with the exception of the smartphone) can be constructed for under $100, excluding the materials for 3D printing. Construction is straightforward, making the schlieren system practical for application in the undergraduate fluid mechanics lab and other project-based learning. We have shown that the smartphone schlieren system can produce quality images of flow phenomena that would otherwise be invisible. The ability to reveal the invisible nature of flows is valuable in an introductory fluid mechanics course and has the potential to elevate student learning, cultivate intuition, and foster an enthusiasm for the subject of fluid mechanics.

Acknowledgements

This work was supported by the National Science Foundation under Grant No. 2021157, which aims to integrate optics into undergraduate research and engineering labs.

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