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Smartphone schlieren and shadowgraph imaging

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ABSTRACT

Schlieren and shadowgraph techniques are used throughout the realm of scientific experimentation to reveal transparent refractive phenomena, but the requirement of large precise optics has kept them mostly out of reach of the public. New developments, including the ubiquity of smartphones with high-resolution digital cameras and the Background-Oriented Schlieren technique (BOS), which replaces the precise optics with digital image processing, have changed these circumstances. This paper demonstrates a number of different schlieren and shadowgraph setups and image examples based only on a smartphone, its software applications, and some inexpensive accessories. After beginning with a simple traditional schlieren system the emphasis is placed on what can be visualized and measured using BOS and digital slit-scan imaging on the smartphone. Thermal plumes, liquid mixing and glass are used as subjects of investigation. Not only recreational and experimental photography, but also serious scientific imaging can be done.

1. Introduction

Schlieren and shadowgraphy are optical techniques for imaging phenomena that are transparent, and thus ordinarily invisible. An introduction to these techniques can be found in any of several available publications [1–6]. They are based on the principle that differences in the refractive index of transparent media, such as the fluids air and water and the solids glass and clear plastic, refract or bend light rays. Simple optical systems can detect these refractions and display them in either a shadowgram or a schlieren image, but the human eye and ordinary cameras lack this ability.

The most prevalent, popular, and available camera today is the miniature digital camera found in the smartphone. Smartphone users now number in the billions [7]. The smartphone camera is primarily used for recreational photography and social media, but it is a powerful imager combined with a potent computer, and it is found in almost everyone's pocket.

1.1. Smartphones as scientific instruments

Over the last few years there has arisen the new field of smartphone scientific instruments, most of which use the phone's camera. Microscopy is well-represented with polarized-light [8], fluorescence [9], multi-mode [10], and direct shadow [11] implementations. One can also have a microscopy add-on such as the Bodelin Technologies ProScope™ Micro Mobile for the iPhone or Samsung Galaxy for about $150US, an inexpensive way for a vast user group to obtain digital microphotography.

Other smartphone instruments, mostly in biomedical testing and analysis, include photoplethysmography [12], imaging and reading cholesterol test strips [13], fluorescence spectroscopy [14,15], bioluminescence and other low-light applications [16], fluorometry for pH measurement in the field [17], ophthalmoscopy [18,19], chemiluminescence [20], and photogrammetry [21]. Reviews of such smartphone instruments are given in [22–24], while a general review of smartphones as measuring instruments is found in [25].

Closer to the current topic are a smartphone instrument that images Mie scattering by microfluidics for pathogen detection [26], smartphone-camera-based laser holography [27], and Particle-Image Velocimetry (PIV) [28]. There is only one apparent publication on smartphone schlieren imaging [29] and none on shadowgraphy.

Finally, citizen scientists with smartphone instruments are able to collect massive datasets on geophysics, astronomy, etc. [30]. There is an important role in Science, Technology, Engineering and Mathematics (STEM) education for experiments using the students' own smartphones, as exemplified in [31,32]. And, although professional scientific equipment is usually very expensive, smartphone add-ons can be an inexpensive way to become familiar with an untried scientific technique. A good example is FLIR 1™, which gives the iPhone owner an introduction to infrared imaging for about $200US, e.g. [33].

1.2. Smartphone, DSLR, and scientific cameras

Optical professionals generally have more suitable cameras in the lab than the miniature cameras in their smartphones. Scientific digital

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cameras can provide much higher pixel resolution and frame rates than consumer-grade cameras [34], but some are so expensive they require a government grant or a mortgage to own.

Intermediate between scientific cameras and smartphones are consumer-grade Digital Single-Lens Reflex (DSLR) cameras. Typically costing $1000US or less, these cameras have selections of interchangeable large-aperture lenses ranging from wide-angle to telephoto focal lengths. They also have large color image sensors, but lack the high frame rates found in some high-end scientific cameras. Nevertheless their lens options make them more suitable for lab use than smartphone cameras [35]. They are also far less ubiquitous, and are too large and heavy to carry around constantly in the pocket or purse.

This paper is not about professional or DSLR cameras for schlieren and shadowgraphy, but rather about what one can do with only the smartphone and some basic accessories and materials. The smartphone camera has some limitations for this purpose that require discussion: Chief among these is its tiny aperture, which makes it unsuitable for traditional schlieren instruments that project a light beam into a camera. A small camera aperture generally vignettes the schlieren beam unacceptably. After beginning with such traditional schlieren optics, this paper will move on to non-traditional schlieren and shadowgraphy where vignetting is not an issue.

Equally troublesome is the fixed wide-angle smartphone lens. (The miniature camera lens is roughly equivalent to a 30 mm focal length lens on a DSLR, where anything below 50 mm is considered to be wide-angle.) Schlieren and shadowgraphy, on the other hand, generally require at least a moderate telephoto lens, since they image a subject whose diameter is typically only 10% of its distance from the camera. When necessary, this problem is solved or at least ameliorated by an add-on telephoto lens for the smartphone.

The smartphone camera user interface provides controls for normal still and video imaging, but not nearly enough control for scientific photography. Fortunately there are software applications (apps) that provide the missing controls, such as ProShot™ (available for both iOS and Android smartphone platforms). Such apps provide full manual control of focus, ISO speed, shutter speed, flash, and white balance, and are inexpensive.

High-speed smartphone imaging is currently limited to video at 120 frames/s (1080p) or 240 frames/s (720p) [28] and a 10 frames/s image burst mode [36]. Many subjects of schlieren and shadowgraph imaging are too rapid to be captured on the smartphone. Some fixed or slower subjects are used as examples in this paper.

In some cases (see Section 3.2), schlieren imaging demands absolute image stability between two or among a series of exposures. A tripod and a custom tripod mount for the smartphone are sufficient, except that a finger-swipe or button-push shutter release is still enough to jitter the camera unacceptably. Depending on the manufacturer, a wireless shutter release may be possible. For the iPhone, the volume switch on the EarPod headphones doubles as a vibration-free shutter release except in burst mode. Fortunately, despite the above issues, schlieren and shadowgraph optics usually provide enough illumination that the smartphone camera's low-light performance is not challenged.

For some of the imaging described below, any small digital camera would work as well as the smartphone camera. However, for slit-scan schlieren (Section 3.5) the smartphone camera, processor, and slit-scan app are able to mimic an expensive scientific camera to which few have access.

1.3. Goals

This paper aspires to reach the potentially-large audience interested in smartphone science, and to enable schlieren and shadowgraph imaging in STEM education, for the hobbyist, and for professionals in other fields who have an interest in this topic. Accordingly, a minimalist approach is taken in the spirit of the amateur scientist [37], LEGO optical mounts [38], and 3D-printed lab equipment [39,40]. Already having the required camera and computer in one's smartphone, not much other equipment or expense is needed for basic schlieren and shadowgraphy. The audience is assumed to have just basic scientific training, though a review of geometric optics at the high-school physics level is encouraged. Examples are given of optical setups and many image results are shown. Not only recreational and experimental photography, but also serious scientific imaging can be done.

2. Experimental resources required

2.1. Smartphones

The present experiments were done primarily using an iPhone 5s running iOS 10 and secondarily using a Samsung Galaxy Core Prime running the Android 5 OS. Neither of these smartphones is the latest available model at the time of writing, but both are typical of recent smartphone camera technology and are able to run the apps needed for schlieren and shadowgraphy. The iPhone has the advantage of 8 vs. 5 megapixels main camera resolution and the clever EarPod shutter release mentioned above. A vibration-free Samsung Galaxy shutter release is accomplished by Bluetooth wireless remote control.

2.2. Apps

When it can be used, the ProShot™ camera control app mentioned in Section 1.2 is very helpful. Unfortunately it does not function in burst mode and it disables the iPhone's EarPod shutter release, so many of the examples to follow were shot without it.

For slit-scan imaging (Sections. 3.4 and 3.5), the Timetracks app by M. Akamatsu or the ScanCamera app by STUDIO-307 are effective on the iPhone and are available at nominal cost from the Apple Store. Similar apps Slit-Scan Camera (J. Rychtář) and Andlisca (M. Aschauer) are available from Google Play for Android-OS smartphones.

2.3. Accessories

As already mentioned, a tripod and a custom tripod mount for the smartphone are required. None of the experiments discussed here can be done hand-held. A Glif iPhone tripod mount was purchased for $15US and a Do-It-Yourself (DIY) mount was made for the Samsung Galaxy. The smartphones, their mounts, and other accessories are shown in Fig. 1.

Next, as described in Section 1.2, the distances involved in schlieren and shadowgraph imaging require a telephoto add-on to the smartphone camera lens in some circumstances. A wide variety of such lenses is available. The lens used here with the iPhone cost under $20US, and is shown in Fig. 1c. No telephoto lens was used with the Samsung Galaxy.

As a small bright light source for schlieren and shadowgraphy, a 5 mm white LED is an excellent and inexpensive choice [6]. Packaged with a coin-sized battery as a keychain flashlight (Photon Micro-Light II™), such an LED is shown in Fig. 1f.

A first-surface spherical reflecting-telescope mirror is required for the only traditional schlieren setup described in this paper (Section 3.1). The example mirror used here and shown in Fig. 1g is 114 mm in diameter and has a focal ratio of f/7.9. It was originally made for use in an economical consumer-grade telescope, and was obtained on the surplus market for $29US [41]. Similar mirrors of the same or smaller diameter were found for sale on eBay with comparable pricing. Note, however, that such a mirror from a professional optics supplier is likely to be at least 10 times more expensive.

Also note that a spherical mirror is required for present purposes, and that a parabolic mirror of the same diameter but shorter focal length will not work. However, Table I of [42] reveals that, for telescope mirrors around 100 mm in diameter and f/numbers greater than 7, the difference between the spherical and parabolic figure essentially vanishes. Thus, for this and other reasons, a longer focal length is always better, provided one has enough space to set up the optics. As a final note, the