Developing optical devices and projects for teaching engineering

Introduction

In order to better meet the demands of students in a competitive higher-education environment, many liberal arts institutions including ours have added new engineering programs and majors. As a part of the process of becoming an interdisciplinary physics and engineering department, and based on prior success at teaching physics with open-ended projects in the upper-level undergraduate curriculum [1], we are studying how these projects can also be used to teach engineering skills and principles. Of particular interest to us are questions related to i) how best to use existing assets (e.g. laboratory equipment, faculty expertise) within a physics and engineering department to create a thriving engineering laboratory curriculum, and ii) to what extent engineering design thinking [2] can be co-taught alongside scientific research skills in interdisciplinary courses. In this our first report on this project, we will describe the process and outcomes of creating a suite of tools and techniques based on optical science for teaching a variety of topics in electrical engineering and mechanical engineering. Each tool is intended for non-expert use and without the need for sophisticated equipment such as vibration-free optical tables, high-power lasers, or low-drift optical mounts.

Three such tools have been created to date, and we report the important details of each. (Further information about the design and implementation of these laboratory tools will be permanently archived on the web, but for now can be accessed by contacting the authors directly.) The three tools described here are image-plane digital holography for measuring material deformation in a mechanical engineering laboratory; schlieren imaging of convective flows using a smartphone and 3-D printed mounts, used in a fluid mechanics laboratory relevant to mechanical engineering and applied physics; and a simple optical communication protocol using a free-space laser and two LabVIEW-enabled computers, for use in an electrical engineering and physics course in wave optics. These tools will benefit students by expanding the undergraduate laboratory curriculum to include non-traditional methods and techniques and by offering starting points for student-led, project-based learning.

We have crafted these optical tools with the following guidelines in mind. First, the final product should be relatively simple and inexpensive to replicate, should others in the community desire to do so. Second, the tool should be prepared with a reasonable and workable degree of functionality (i.e. a hologram of a deformed metal beam can be collected and studied), but wherever possible the tool should also be open and available for student projects to add new features, push the measurement limits, or explore other use cases. And third, the tool should encourage students to engage with and tolerate some amount of ambiguity. In other words, the utilization of the tool has not been previously optimized and prescribed for the student using it, but instead the student will have to reach a stated goal without necessarily having a clear map of how to do so. The latter guideline stems from a desire that aspects of design thinking be present, whether explicitly or subtly, in the engineering laboratory curriculum, with the ability to tolerate ambiguity understood to be an essential skill of good designers [2].

Methods and Results

In this section, we describe a few salient features of the design of the three optical tools and provide initial comments about their utility. First, we consider digital holography as a means of quantitatively visualizing mechanical deformation. Broadly, the technique of digital holography involves interfering two laser beams onto a digital imager such as a CCD camera. One laser beam will have interacted with an object to be studied, and the other will serve as a reference, unaffected by the presence of the object. Typically, the use of a numerical computation to “reconstruct” the electric field at the location of the object is required in order to display an image of the object on a computer screen, but we have avoided this step by choosing image-plane holography. Here, a lens is used to cast a (real) image of the object directly onto a camera, and an interference pattern that modulates the image can be read off without any computation and used to determine the phase of light reflecting from the object. This system is diagrammed in Fig. 1A, and Fig. 1B provides a photo of the real apparatus. Hanging a weight off the object, which in this case is a thin beam formed from aluminum or a similar metal, bends the beam and creates a set of easily visible interference fringes across the image. By counting the number of fringes and equating each to half of the laser wavelength (633 nm), the displacement of the metal I-beam is measured in real time. We found excellent quantitative agreement between the observed deformation under weak loads (typically 1.5 μm at the maximum) and a textbook equation that depends upon the moment of inertia, the modulus of elasticity, and the applied force. This tool will be used in a junior-level mechanical measurement techniques course as an alternative to other traditional methods (i.e. strain gauges).

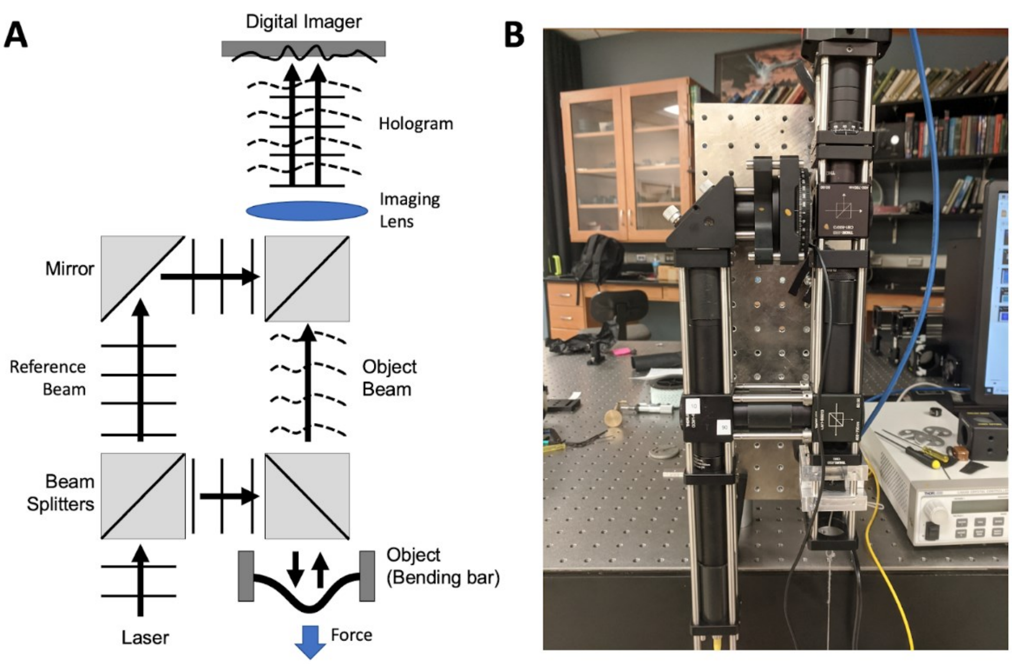

Fig. 1: A diagram (A) and photo (B) of the digital holography apparatus.

Next, we describe a smartphone-based schlieren imaging system. The system uses only two components, a smartphone that serves both as light source (via its flash) and imager, and a concave mirror located at a distance of two times its focal length from the smartphone. A source of convective flow (e.g. a candle or air duster) can be placed in front of the mirror, allowing the flow to be visualized via the changes in refractive index that occur alongside the spatially varying density, and the image is sharpened by placing a small aperture (e.g. black electrical tape with a small pinhole) in front of the flash to limit the aperture, as well as to serve as a “knife edge” that covers a portion of the camera. To rigidly space and mutually align the smartphone and curved mirror, we have designed a single mounting apparatus using 3-D printed materials and standard fasteners and adjusters available from a hardware store. A model and photo of this apparatus are shown in Fig. 2. Note the schlieren image of a handheld lighter is visible on the smartphone screen. We have used this tool as a lab exercise and as a project staring point in an interdisciplinary fluid mechanics course taken by mechanical engineering, applied physics, and physics students.

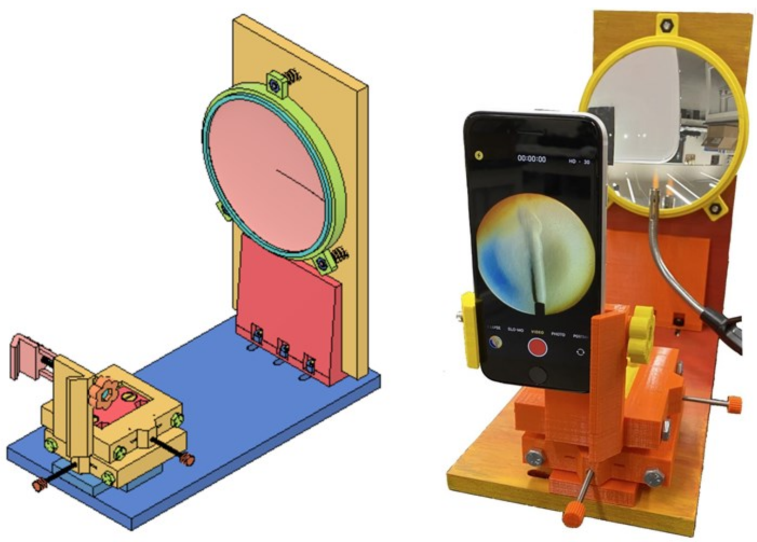

Figure 2: Model (left) and photo (right) of the schlieren imaging apparatus.

The third and final tool we describe is optical communications via a free-space laser beam. Here we emphasize amplitude-shift-keying, an optical analog to AM radio, as the simplest means of transferring information via a laser. Two LabVIEW-enabled computers with input/output voltage channels are able to send and receive messages by changing the diode laser’s drive current, thereby changing its power, and reading out those changes by photodetection and subsequent digital comparison to a threshold value. Error-free, one-way communication was observed at kilobit-per-second speeds, limited in speed by the choice of laser diode current source. Significantly faster communication speeds were also observed using frequency shift keying, but at the expense of greater system complexity. Both systems will be used as a lab exercise and as a project starting point in a junior Optics course taken by physics and electrical engineering students. Possible project extensions of this system include implementing two-way communications, implementing remote time transfer and clock synchronization, and simulating atmospheric turbulence effects by inserting frosted plates into the laser beam.

Conclusions

We have presented a few of the design considerations of advanced laboratory tools that are being used in the laboratory curriculum of an interdisciplinary engineering and physics department. Specific plans and schematics are available from the authors upon request. Future work on this project will emphasize the experiences of students and faculty members that learn from or teach with these tools, including the use of assessment tools to study the effects of these tools upon the students' engineering design skills.

Acknowledgements

This work is supported by the NSF Division of Undergraduate Education (award # 2021157) as part of the IUSE:EHR program.

References

1. R. C. Hilborn and R. H. Howes, "Why many undergraduate physics programs are good but few are great," Physics Today, vol. 56, no. 9, pp. 38-44, 2003.
2. C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey, and L. J. Leifer, "Engineering design thinking, teaching, and learning," Journal of Engineering Education, vol. 94, no. 1, pp. 103-120, 2005.