Involving Undergraduate Students in Research through the Development of Low-Cost Optical Instrumentation

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Abstract

Engineering schools that primarily serve undergraduates are an important part of our system of engineering education. Their students are usually taught by faculty rather than teaching assistants, and higher faculty teaching loads enable more continuity in course sequences. Since students benefit when faculty tie class work to new applications, it is important that faculty perform research even in primarily undergraduate institutions. Research can be challenging with high teaching loads and a lack of graduate assistants. This paper describes the author's approach in conducting research with undergraduates at NYIT. Together, the author and his students utilized solid modeling, 3D printing, machining, and commodity electronics to construct a digital holography system. Such instrumentation projects are ideal for introducing students to real engineering challenges while also enhancing faculty research capabilities. The holography system is used for the author's research and has also proven useful for visualizing flows encountered in undergraduate fluid dynamics courses.

Keywords

undergraduate research, primarily undergraduate institutions, 3D printing, holography

Introduction

Engineering schools that primarily serve undergraduates are an important part of our system of engineering education. Students at these schools are more often taught by faculty rather than teaching assistants, and the higher number of courses taught by each faculty member helps students by maintaining continuity in how courses are taught within course sequences.

However, these schools are not without their disadvantages. Students benefit from faculty who can tie class work to cutting-edge applications. It is therefore important that faculty be engaged in research even in primarily undergraduate institutions. This requirement can be difficult to meet, as faculty at these institutions do not necessarily have help from graduate students and teaching loads are higher.

This paper describes the approach taken by the author to conduct seed research with undergraduates. Together, the author and his students utilized parametric solid modeling, 3D printing, conventional machining, and commodity electronics to construct a number of useful instruments. One of these instruments, an optical system for digital holography, is described. This system, which was original conceived as a way of monitoring droplets and sprays, has also proven useful for the visualization of flows encountered in undergraduate fluid dynamics and propulsion classes. The students have therefore contributed to hardware that enhances the experience of future students.

Research and Engineering Education

Any engineering education must include a component where students experience real phenomena and real devices corresponding to the discussions in their textbooks and lectures. Although laboratory courses and specific design courses fill some of this need, involving students directly in the design and *construction* of new devices is a particularly effective route to provide this experience. In the process students get to see, firsthand, how things that they conceived work and they are forced to think about how what they have learned applies to a given situation. When things do not work as planned, they need to investigate in order to understand why – perhaps by performing new experiments, perhaps by looking more closely at the theory. This process makes them better engineers. If they graduate to a position where they only handle designs on paper, they will still be able to draw on this experience and create better designs.

This approach is often embodied in a capstone design course. In such courses, hands-on work gives the necessary experiential learning while also teaching students about project management and allowing educators to better assess their learning[1]. This approach can been taken further – undergraduates can be directly involved in faculty research to allow them to experience an engineering group environment[1]. Here, the author reports on his experience with this approach, where the students were asked to help design and build optical instrumentation.

Instrument design and construction is a particularly effective way to expose students to many of the theoretical and practical aspects of engineering. Instruments are precision products and the requirements for good product design are especially important in their development. Instrument design is also directly beneficial to faculty, as access to high-quality but inexpensive instrumentation is especially helpful as they try to break into new research areas.

Telenko et al.[2] have provided several examples where teaching and research have been successfully integrated, relieving some of the conflict between space and time requirements for these two activities. Instrument development could also serve as an example. The key requirement, of course, would be that the course not feature the design of the same instrument each time. The engineering group environment described by Sergeyev at al[1] (mentioned above) is probably most effective, where a small group of students is guided by a faculty researcher to complete interrelated parts of the same project. In this environment, the students serve as sort of apprentice engineers, completing research tasks while learning, as necessary, along the way.

The next section describes digital holography and subsequent sections discuss how a digital holography system was implemented at low cost.

Digital Holography

Holography is a means of recording light in such a way that the entire wavefront, with both amplitude and phase, can be reconstructed. Such a wavefront behaves like the light originally present in the scene being recorded. Large-area film holograms can be used to capture three-dimensional images that can be viewed from different locations like the original objects in the scene.

In conventional holography, light from a coherent monochromatic source is used to illuminate the scene of interest. A reference beam from the same source is also used to illuminate the film.

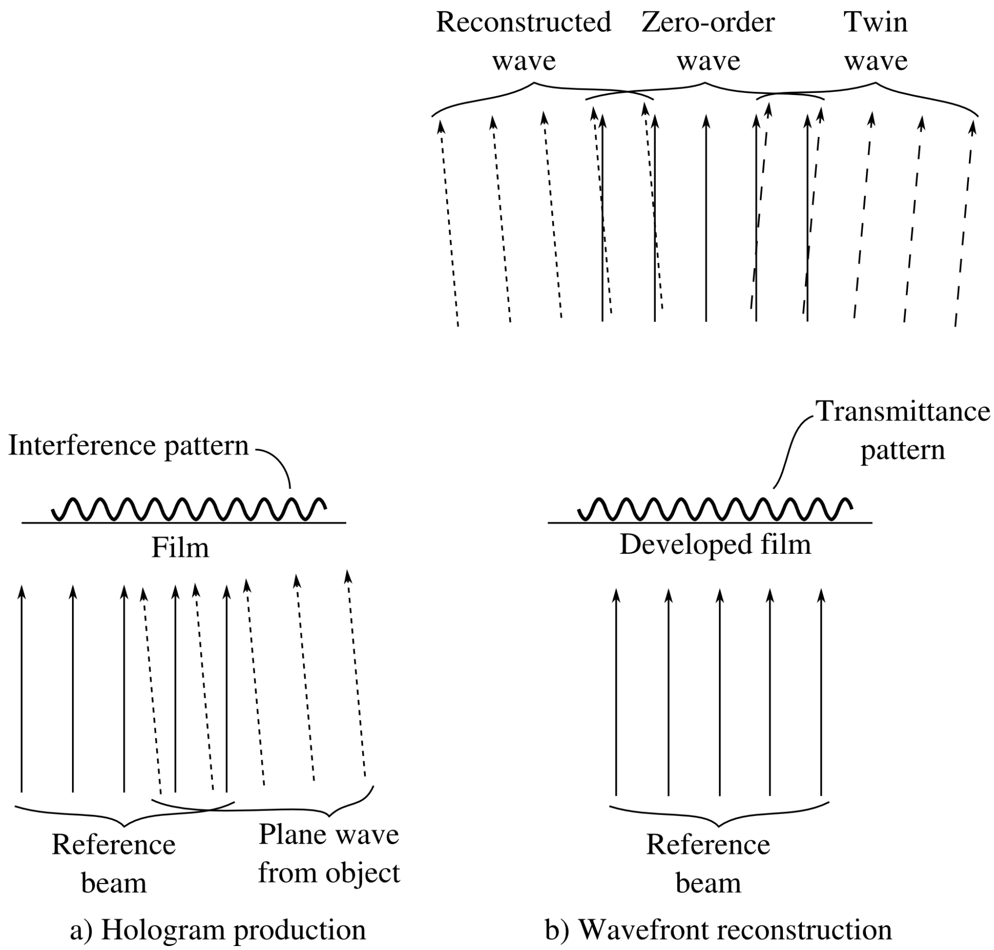


Figure 1: a) Production and b) reconstruction of a hologram from a single plane wave emanating from the object of interest.

Interference between the reference beam and the light incident from the scene produces fringes on the film. If the developed film is reilluminated by the reference beam, the incident wavefront is reproduced as the reference light is diffracted at the fringes.

To see how this works, consider the situation shown in Figure 1. There we have a monochromatic plane wave incident normal to our film that serves as our reference, while a second plane wave of the same wavelength is incident from our object. In general, the plane wave from the object is incident at an angle, so when the two waves interfere (they must be coherent), they produce a sinusoidal intensity variation which is captured on the film. After the film is developed, it acts as a transmission diffraction grating. Illuminating the film with a reference plane wave reproduces the original plane wave, along with a twin wave at the opposite angle and a zero-order wave that simply passes through the film undiverted.

If we repeat this thought experiment with a point source at the object producing spherical waves, the interference pattern (hologram) will form a Fresnel zone plate[3]. In that case, illumination by a plane wave produces both converging and diverging wavefronts corresponding to the desired and twin wavefronts in the plane-wave example. The twin image is therefore not focused in the same plane as the desired wavefront with a plane-wave reference.

The complete wavefront from the object can be decomposed into either plane waves or spherical waves, so as long as the interference patterns are properly captured on the film the original wavefront can be reconstructed. From the plane-wave point of view, we see that waves incident at larger angles relative to the reference beam produce finer fringes. The effectiveness of the film in recording these finer fringes may limit resolution, depending on the granularity of the film.

With its ability to reproduce a complete wavefront, holography allows manipulation of that wavefront after the scene has been captured. Lenses can be used to refocus the image. The lenses can also be translated within the wavefront to view the scene from different points of view. These properties allow viewers to see three-dimensional features of the scene, such as varying amounts of occlusion, as they view the reconstructed wavefront.

The disadvantages of holography are primarily related to the manner in which holograms are recorded. Since interference fringes are recorded directly, small shifts in the object during film exposure (shifts as small as one-quarter wavelength for reflected light) can wash out the fringes. Long exposure times therefore require vibration isolation even for still scenes. The object must also be illuminated with coherent light, although techniques exist for employing short-coherence-length light. This work, in fact, employs one such short-coherence-length technique, which will be discussed later.

In digital holography, the film is replaced by an image sensor and the reconstruction process is completed numerically. This change brings a number of benefits. First, like other forms of digital photography, holograms can be recorded and processed in near real time. More important, though, are the benefits of numerical reconstruction. In conventional holography we can use lenses to alter the reconstructed wavefront. In digital holography, such lenses can be implemented numerically. In that sense digital holography is much like software-defined radio – complicated schemes for processing the signals can be implemented in software on a general purpose computer rather than relying on dedicated and expensive hardware. Digital holography could therefore be called software-defined optics.

Since the wavefront is reconstructed in software, digital holography also has direct access to wavefront phase data. Phase data are typically utilized for visualizing transparent objects, such as in phase-contrast microscopy[4,5] or interferometry through fluids[6]. With digital holograms, conventional flow visualization techniques, such as interferometry, schlieren, and shadowgraph imaging, can all be implemented in software. Interferometry and shadowgraph imaging are utilized in this work.

Digital holography is not, however, without its disadvantages compared to conventional holography. The minimum pixel sizes in available image sensors are larger than the granularity of photographic film, so waves incident from far off axis cannot be properly captured. In addition, although the pixels do average such fringes out to some extent, there may still be aliasing in the reconstruction if off-axis illumination is present. The situation has been helped in the past few years by the drive to make cell-phone cameras ever smaller. Typical pixels sizes for silicon focal-plane arrays had earlier been on the order of 5 to 10 μm. In this work, we utilized an inexpensive cell-phone camera with 1.4 μm pixels.

The High Cost of Optical Components

For researchers trying to construct a new optical system, the cost of optics and optical mounts can be daunting. At the time of writing, a one-inch square aluminum first-surface mirror has a cost of $50. A tilt mount for the mirror with a base has a cost of about $75. Costs for the mounts are typically more than those of the optics themselves. Even a simple optical system can become very expensive very quickly.

Given the stability requirements for holography, it might seem that one must simply find a way to pay for proper mounts in order to put together a working system. In fact, much to the author's surprise, working mounts could be 3D printed from polymers like PLA and ABS. This route provided an excellent means to quickly prototyping optical systems and ensuring student involvement. Students could design, print, and test optical mounts in a matter of a day or two. These were then used to mount optics that were purchased from a commercial vendor.

Student-Developed Digital Holography System

This section begins with a detailed description of the current digital holography system. A discussion of the student-designed parts and subsystems follows in the next section. A diagram of the optical system currently employed is shown in Figure 2. The optical arrangement is a Mach-Zehnder interferometer. Collimated light from a pulsed 905 nm semiconductor laser passes through a cube beam splitter, forming a measurement beam and a reference beam. The measurement beam is folded back with a pair of fixed mirrors. The sample of interest can be placed anywhere in the measurement beam path, but the preferred location is closest to the focal-plane array. The reference beam is folded back by a pair of mirrors mounted on a linear stage. The linear stage allows the total path length in the measurement and reference arms to be matched. This matching is necessary because of the short coherence length of the pulsed laser.

When the path lengths are nearly matched, interference fringes form on the focal-plane array. Though it is not immediately evident in the diagram, the fixed mirrors can be adjusted in position and orientation so that there is an angle between the measurement beam and the reference beam when the two overlap on the focal-plane array. This angle produces an angular separation between the reconstructed measurement beam, its twin, and the zero-order beam. Spatial filtering[3] is then performed during the reconstruction to eliminate the twin and zero-order beams.

For the measurements reported here, the laser was an OSRAM Opto Semiconductors 905 nm, 25 W Pulsed Laser Diode, model SPL PL90 driven by a pulse-forming network constructed on a custom printed-circuit board. The pulse-forming network was designed to drive the laser at nearly constant current over a 50 ns interval after receiving a trigger pulse. The laser output was spatially filtered by coupling it into a single-mode optical fiber, the output of which was collimated with a cemented doublet lens. This configuration yields a clean, Gaussian beam. The author has also had success using the laser directly, without spatial filtering, to increase the available intensity at the expense of beam uniformity.

The focal-plane array used for the measurements was a Raspberry Pi NoIR camera, which is constructed from an OmniVision OV5647 camera module without an infrared filter. The small lens in the camera module was removed. The array in the module has 2592 by 1944 pixels which

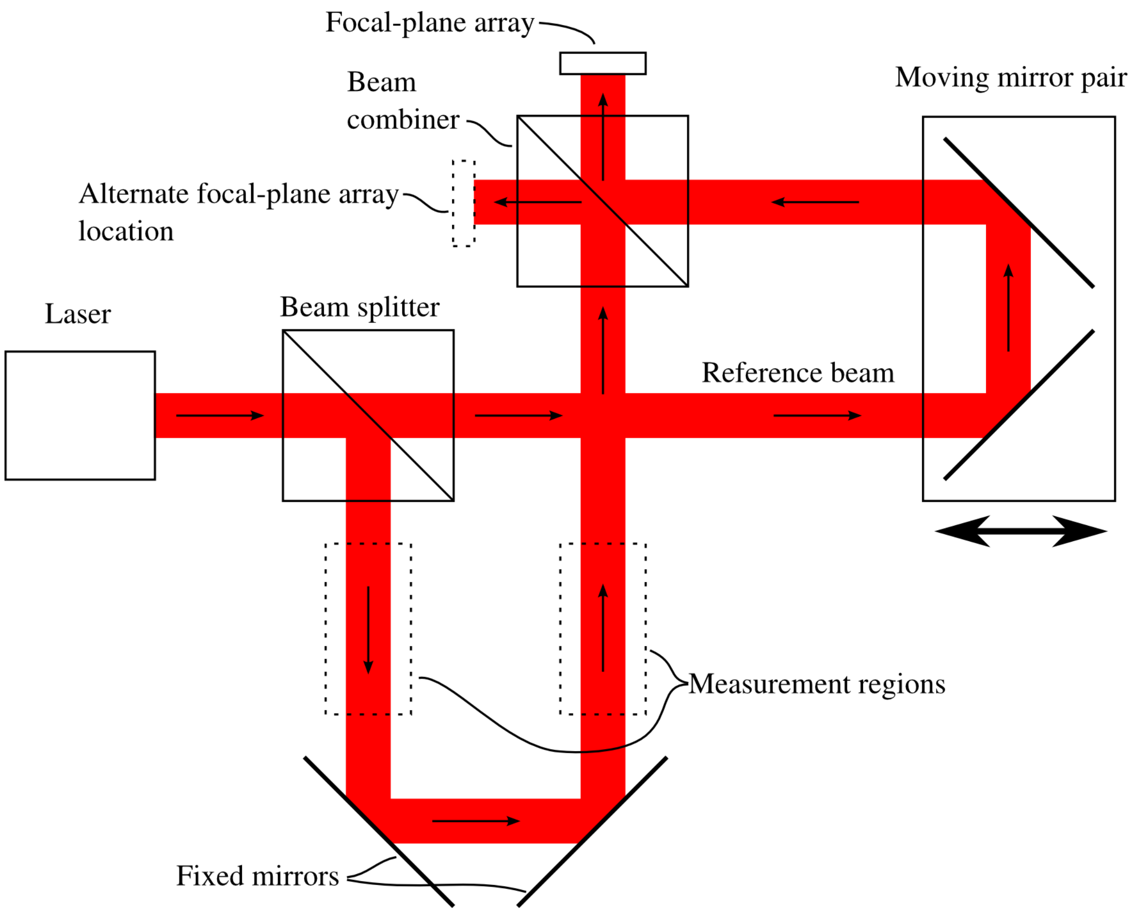


Figure 2: Digital holography system for collecting short-coherence-length holograms in transmission with a pulsed laser.

are 1.4 μm on a side. The camera can be used to capture still images at the full resolution about every two seconds, or lower resolution video at higher rates. For this work, the full resolution images were collected.

When collecting holograms, the camera was set to provide raw, uncompressed data, so that artifacts from lossy compression would be avoided. These raw data are individual 10-bit pixel values. The camera module features per-pixel color filters in a Bayer pattern. For the 905 nm laser wavelength, each of the filter types (red, green, and blue) shows significant transmission that would normally be suppressed by the camera's infrared filter. It is therefore possible to calibrate each filter type (and potentially even each pixel) and recover a hologram with points spaced at 1.4 μm. In this work, we instead binned each square of four pixels in the Bayer pattern (blue, green, green, and red) to generate a hologram with points spaced at 2.8 μm. This binning halved the maximum off-axis angle that could be collected without aliasing, but this was not a limitation for the present optical configuration.

The camera module was directly coupled to a Raspberry Pi model B single-board computer. Initially, the collection and processing were all completed on this inexpensive computer. Full hologram reconstruction could be completed in about 30 seconds with GPU acceleration of the Fourier transform calculations. Later, to enhance the frame rate of the system as an aid in alignment, the software was modified to have the Raspberry Pi collect images and send them over the wired network to an attached Intel Core i7 laptop computer. This computer would then complete the reconstruction. In this configuration, the collection, transfer, and reconstruction times together yielded a frame period of about three seconds. This period is short enough that the alignment can be adjusted using the reconstructed images as feedback.

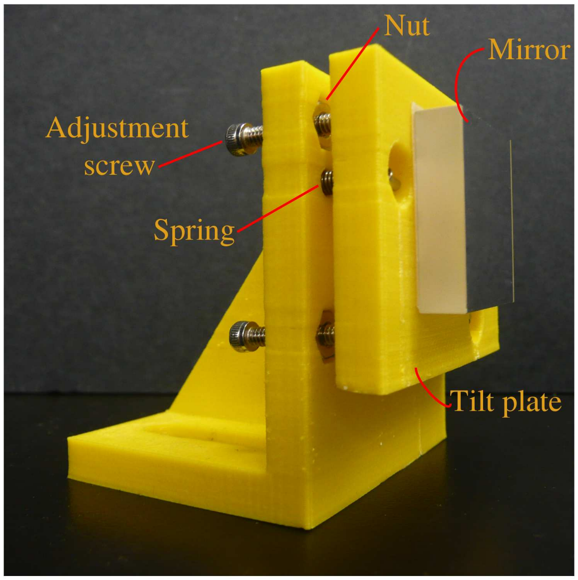
One difficulty with using the Raspberry Pi camera module was that the module has a rolling shutter. That is, the pixels are not all exposed at the same time. Through experimentation, we found that if the exposure time was set to 70 ms in still mode and the laser was triggered at 65 ms, all of the pixels would be exposed by a single pulse. To coordinate the laser triggering with the image collection, we configured the Raspberry Pi to direct the flash signal of the camera module to one of its general-purpose input/output pins. A microcontroller connected to this pin was used to trigger the laser after the required delay.

Construction Details

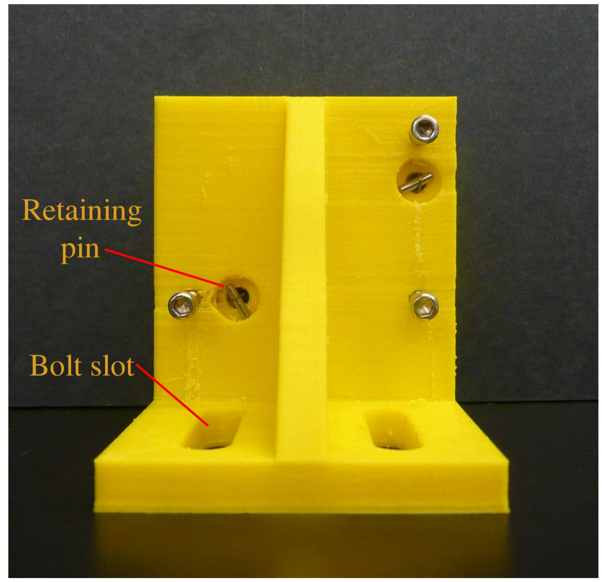
The undergraduate mechanical engineering students involved in this project contributed in two main areas. First, they designed and 3D printed the mounts for the mirrors, beamsplitter, and camera. Second, they designed and built a motorized linear stage for the moving mirror pair.

The students developed most of their designs using the parametric solid modeling software Inventor from Autodesk and SolidWorks from Dassault Systèmes. In either case, the parametric nature of the software makes it easy to create different sized variants of properly defined parts. For example, it is easy to adjust the height at which the optics are held without redesigning the parts if the design beam height is changed.

Many of the mounts featured tilt adjustments that were actuated using threaded adjuster screws. While it is possible to generate threaded components with 3D-printed plastic parts, we opted



a)



b)

Figure 3: Mirror mount manufactured by 3D printing. a) side view b) back view.

instead to incorporate metal nuts and bolts wherever threads were necessary. This approach adds little in cost and creates good mounts with fine threads that do not shed plastic debris due to wear.

An example mount is shown in Figure 3. This is a tilt mount for a one-inch square mirror. It has three adjuster screws. Ordinarily the corner screw, shown on the bottom right in the back view of the mount, is left fixed while the remaining two screws are used to independently tilt the mirror horizontally or vertically. All three screws can be adjusted together to move the mirror normal to its reflective surface.

The adjuster screws are 0.75-inch-long #4-40 bolts. The bolts thread through nuts that are recessed into hexagonal holes in the front of the fixed part of the mount. The mirror is attached to the tilt plate using double sided tape. The tilt plate is pulled against the screws by a pair of springs that are stretched between retaining pins recessed into the two parts. The ends of the screws rest in conical indents on the back of the tilt plate. These indents keep the tilt plate from sliding sideways across the ends of the adjuster screws.

The mounts used in this work were printed from ABS filament by fused filament fabrication using a Makerbot Replicator 2X 3D printer. Model slicing was performed with Makerbot's Makerware software. The slicer was set to 0.3 mm vertical resolution and three shells were used.

As mentioned above, the students also designed and built a motorized linear stage for the moving mirror pair. The stage is shown in Figure 4. A stepper motor (1.8°/step) drives the lead screw through an 8:1 gear reduction. The lead-screw pitch is 24 turns per inch, and the stepper is driven with a microstepping driver that provides 32 microsteps per motor step. The entire drive train therefore delivers 20.7 nm steps, but wind-up and stick-slip conspire to prevent the achievement of this level of precision. These limitations prevent the stage from being useful as part of a

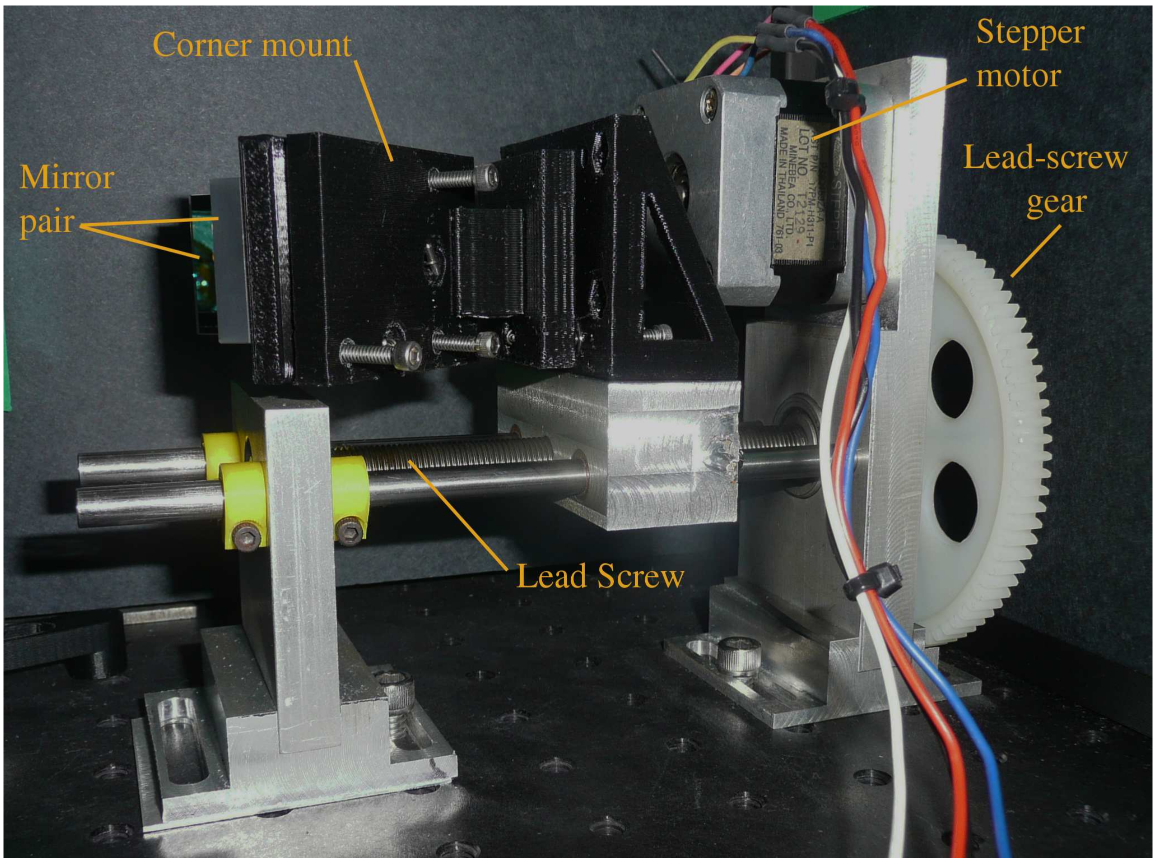


Figure 4: Stepper-motor-driven linear stage for the moving mirror pair.

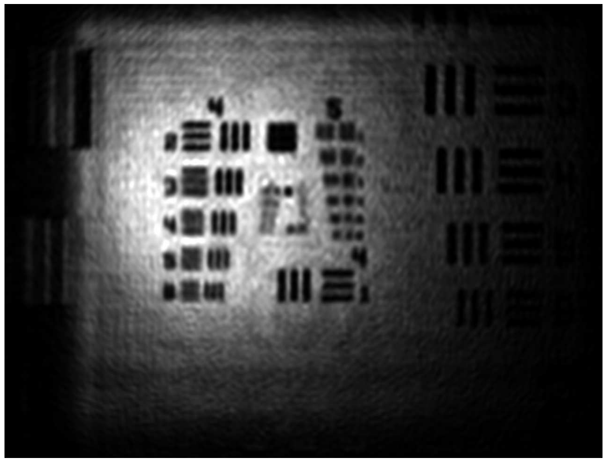


Figure 5: Reconstructed image of a USAF 1951 resolution target. Lines in element 2 of group 4 are 28 µm wide.

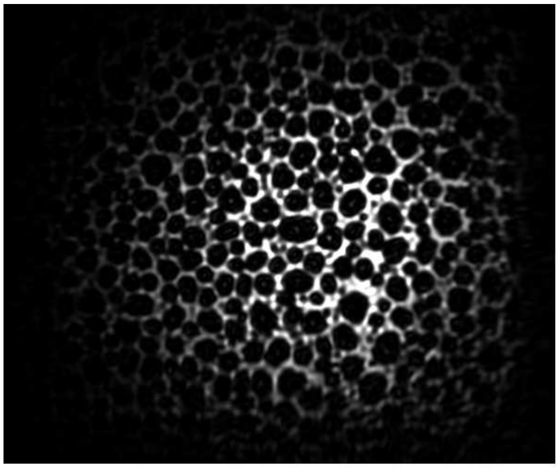
stepped-scan interferometer, but scanning the mirror pair readily produces interferogram envelopes that are useful for obtaining zero path difference between the measurement and reference beams. That is, even though the individual steps are randomly distributed because of the mechanical limitations, we still see the depth of the fringes by noting the intensity differences between the randomly encountered maxima and minima as the mirror is moved over a short distance.

The mount for the mirror pair (labeled "corner mount" in the figure) allows the angle between the mirrors to be adjusted independently of the collective orientation of the pair. If the angle between the mirrors is 90° in the horizontal plane, they reflect the beam back in the incoming direction (though displaced sideways), regardless of the horizontal orientation of the mirror pair relative to the incoming beam. Further immunity to the pitching of the pair in the vertical direction could be achieved by using a third mirror to put together a corner cube retroreflector and reorienting the mirrors so that the incoming beam hit all three surfaces. In the current configuration, an additional tilt adjustment is provided between the mirror pair and the point where the mount attaches to the linear stage. This adjustment allows the tilt of the pair to be adjusted collectively.

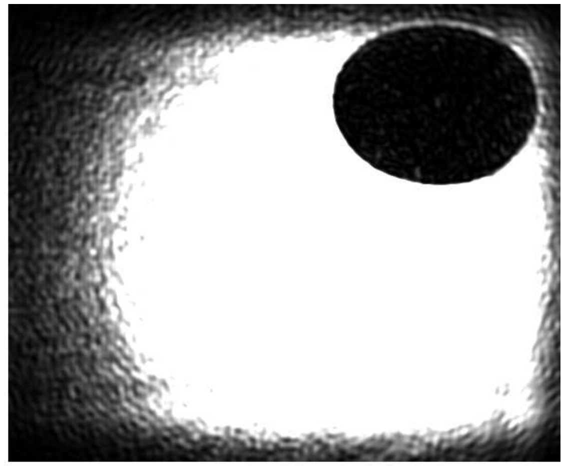
Experimental Results and Discussion

In the configuration described above, the system provides backlit images for a beam diameter about equal to the 2.7 mm height of the focal-plane array. It was designed for imaging droplets, and with objects at 70 to 100 mm from the array it provides sufficient resolution to resolve droplets down to less than 25 µm. The resolution of the system is demonstrated in Figure 5, which shows a reconstructed image of a USAF 1951 resolution target. Element 2 of group 4, visible in the upper left center of the figure, has 28 µm-wide lines and spaces, and it is resolved. Note that the better resolution for the horizontal direction in comparison with the vertical direction is consistent with the aspect ratio of the array – the effective aperture is wider in the horizontal direction so the diffraction limited spot size is smaller in that direction.

Two backlit droplet images collected with the system are shown in Figure 6. The left image



a)



b)

Figure 6: Backlit droplet images. a) Water condensation and coalescence on a glass plate. b) A single water droplet suspended by acoustic levitation. Its horizontal diameter is 0.5 mm.

shows water that has condensed on a glass plate, droplets of which have coalesced. In the backlit configuration, the droplets appear dark except for bright spots in their centers where some of the light leaves in the original beam direction. The right image shows a single larger water droplet (about 0.5 mm in its horizontal diameter) suspended by acoustic levitation. This droplet is suspended near the edge of the beam and we see diffracted light around its top edge.

Digital holography has important advantages over conventional imaging when monitoring droplet interactions. Droplet collisions and droplet shattering can result in secondary droplets that move out of the image plane. In normal microscopy, these secondary droplets would move quickly out of focus due to the limited depth of field. If holographic video is instead collected, each frame can be refocused as many times as necessary to image all of the secondary droplets.

Finally, digital holography provides direct access to phase information about the wavefront. Figure 7 shows a color-mapped phase image of a 0.61 mm-diameter air jet formed by a converging nozzle exhausting into room air. The flow is from left to right, and the flow is directed slightly downward. The upstream pressure for the nozzle is 80 psig, so the initially sonic jet is underexpanded. The resulting wave structure is visible in the phase image.

Conclusions and Future Work

The work described here is an example of how instrument design can be used to give undergraduates hands-on engineering experience while supporting faculty research needs at a primarily undergraduate institution. Together, the author and his students developed an inexpensive system for performing digital holography, and this system has been applied to two-phase flows and compressible flows.

The undergraduates involved in this work served as paid research assistants, but this approach could also be extended to special topics courses and capstone design courses. For the digital holography work, the author anticipates utilizing a portable version of the system for in-class demonstrations of compressible flows.

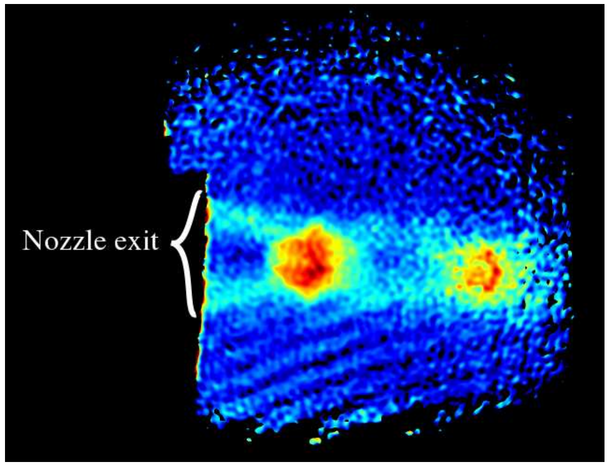


Figure 7: Phase image of an underexpanded sonic jet formed by a converging nozzle with a 0.61 mm-diameter throat. Flow is from left to right.

Acknowledgments

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References

1 A. Sergeyev, M. Azizi, and S. B. Lakshmikanth. Senior design capstone project: Design and development of mount structure and end-effector for automated robotic stacker. *ASEE Annual Conference & Exposition*, (Paper ID #14435), 2016.

2 C. Telenko, A. S. Jariwala, C. Saldana, T. Sulchek, S. K. Yee, W. C. Newstetter, and T. Kurfess. Examples of synergies between research and hands-on design-based learning. *ASEE Annual Conference & Exposition*, (Paper ID #15472), 2016.

3 Myung K. Kim. *Digital Holographic Microscopy*. Springer, 2011. ISBN 978-1-4419-7792-2.

4 C. J. Mann, L. F. Yu, C. M. Lo, and M. K. Kim. High-resolution quantitative phase-contrast microscopy by digital holography. *Optics Express*, 13:8693–8698, 2005.

5 M. K. Kim, L. F. Yu, and C. J. Mann. Intereference techniques in digital holography. *Journal of Optics A–Pure and Applied Optics*, 8:S518–S523, 2006.

6 D. Igra and K. Takayama. Experimental investigation of two cylindrical water columns subjected to planar shock wave loading. *Journal of Fluids Engineering*, 125:325–331, 2003.

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