Developing a classroom system to visualize wave optics phenomena

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ABSTRACT

While mathematical analysis of wave physics involves Complex algebra and beyond, waves are also very familiar objects in everyday life. The Wave Optics Visualizer is a water basin with a unique wave generating device that takes advantage of the familiar water wave to produce and visualize a wide range of wave physics phenomena. Many visually interesting demonstrations can be produced and these can also be directly related to classroom themes for multiple academic levels. The device is carefully designed to perform its main functions as well as to be portable and connectable to classroom technology for use in classrooms and other locations for demonstration. The Wave Optics Visualizer is based on a rolling cart with three main systems; the water transfer system, the wave generator and the visualization system. The water transfer system allows water to fill the basin as well as to be easily drained to a holding tank for transportation. The wave generator is a computer controlled array of sixteen independent actuators, programming allows multiple wave interactions to be produced. Finally, the visualization system consists of a machine vision camera and LED illumination, this system allows excellent wave visibility and the ability to freeze or slow the observation by matching the camera frame rate to the wave frequency. The Wave Optics Visualizer provides an effective and portable tool for demonstrating and teaching the complicated phenomena of wave physics.

1. STATEMENT

The Wave Optics Visualizer has been developed with the specific purpose to serve Undergraduate learning at the University of Rochester's Hajim School of Engineering and Applied Science. The project was conceived in the Institute of Optics Teaching Labs, where the Institute is a department of the Hajim School. Funding for the development and construction of the project was provided by a Sykes Award for innovation in Undergraduate curricula. It has been noted that many student struggle with their second year course work in Optics especially regarding optical wave physics and the associated math. The purpose of the Wave Optics Visualizer is to provide a system for generating wave optics phenomena that can be directly observed and interacted with in hopes of improving learning outcome performance.

2. INTRODUCTION

A need for innovative methods for teaching wave physics has long been recognized in Optics Education[1,2,3]. According to many years of discussion in the Institute of Optics Undergraduate Committee, students generally find geometrical optics relatively intuitive and the math applied to geometrical optics more familiar. Wave optics concepts, however, are more difficult and a significant proportion of students are less comfortable with the vector and complex math involved in the wave physics analysis for optics.

It was hypothesized that a lack of demonstration directly showing wave interaction may cause a gap in learning due to difficulty in creating a mental model of wave interactions for some students. In order to provide a physical system that can produce demonstrations to match math applied to wave physics, the Wave Optics Visualizer has been developed.

Project development began with conceptualization as in important and innovative project for which to seek Sykes Award funding from the Hajim School of Applied Science and Engineering at the University of Rochester. The proposal for funding was accepted and an $8000 budget was allotted for June 2021 through June 2022. The following sections will outline the various steps of development and construction of the device and initial efforts to deploy the system for teaching and outreach.

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3. INVESTIGATION

Early work centered on investigating the needs that this type of system can fulfill and what technical aspects of the system should be specified and developed to meet these needs.

The most direct application in the Optics and Optical Engineering curriculum was identified in the Optics 261 Interference and Diffraction course. This course is frequently a difficult academic point for Optics students. Interference and Diffraction topics and the associated math analysis are incrementally more difficult to understand than those in geometrical Optics and student performance is notably lower. The main objective is that by exposing students to a real, physical and interactive system that shows wave phenomena relevant to interference and diffraction, there will be improvement in student success in OPT 261. Therefore, the system would be designed to create demonstrations where interference and diffraction of waves can be seen and measured. Exact methods for evaluating the success of this objective must be further developed, but can be associated with information collected for ABET accreditation at the Institute of Optics.

Additional needs that the Wave Optics Visualizer can fulfill would include providing an engaging demonstration and workshop for first year students in the Optics 101 course. Here students are exposed to a wide range of Optics topics with limited Math and Physics requirements. Interesting and interactive demonstrations are an important aspect of the course. Therefore, the system would provide demonstrations that are visually interesting and interactive. Students and instructors must be able to change the demonstration in real time, and ideas of the students would be able to be tested in that moment. Overall, the system would have a simple, easily understood and reliable control system.

Also, the system would serve as an exciting outreach demonstration for audiences with varying background in Optics or no background in Optics. Most individuals associate light with a wave and therefore a device that produces real time interactions of waves in motion is engaging and can bring familiarity to Optics demonstrations.

Finally, advanced level wave concepts may be added to the systems functions, however, this would be a secondary focus. Ideas included in the investigation of advanced concepts were resonant cavities, phased systems and spatial measurement by reverberation analysis.

At this stage it had been determined that the system must have the ability to produce plane waves in addition to two independent point source waves which can be easily moved relative to each other. Advanced level concepts would require additional functionality.

4. RESEARCH

Following the investigation to identify important functional aspects of the Wave Optics Visualizer, research was completed to study the technical aspects of similar systems that exist. Ideas that seemed promising for further development were identified in this phase. Also, only ideas related to the wave generating system were considered at this time. Practical construction and use of the system would be considered in later phases.

Devices under the name “ripple tank” are commonly available for the purposes of demonstrating wave physics[4,5,6]. While their level of sophistication does not meet the requirements for this system. Valuable information can be found in the design of their wave actuators. For example, a sphere shaped actuator on an extended arm can produce a point source wave radiating in all directions when oscillating vertically (in the direction transverse to the propagation of the wave). A long bar can produce plane waves when oscillating horizontally (in the direction of wave propagation).

If a combination of the plane wave generator and two movable point source generators were to be integrated, the functional requirement of the system would be met. Therefore these designs were selected for further development.

Next, the method of actuating the wave generators was investigated. It was found that in most existing systems, a simple rotating electric motor and linkage were used. This provides on/off functionality with perhaps control of frequency through adjustment of the motor speed. However, this method was determined to be too limiting in terms of functionality for a system that should have multiple adjustable parameters. Therefore, the methods of actuation that were selected for further development were the stepper motor and the voice coil actuator.

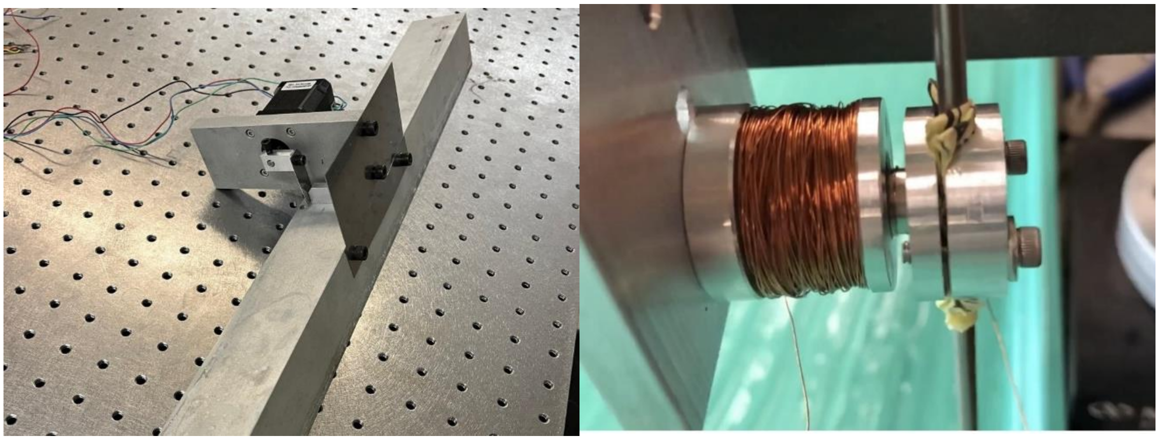


Figure 1. Stepper motor actuator (left) and voice coil motor actuator (right) prototypes.

To meet the technical requirements of a plane wave source and two movable point sources, the system would require the integration of three stepper motors or three voice coil systems, or perhaps some combination of each type of actuator. Both designs were selected for development.

5. DEVELOPMENT

Development of the prototype wave actuating systems involved design and fabrication of a stepper motor based system, and a voice coil motor based system. In order to test the new systems, a shallow tray was used as a water basin and typical optical component mounting hardware would support the actuator systems.

The stepper system would use a commercially available motor; various electronic interfaces would also be tested. The design focus for the stepper motor system more heavily involved design of the mechanical linkage to the wave actuator and work on interfacing the motor with various controllers to create a real time control program. The most successful stepper motor design was a plane wave actuator with a large aluminum bar dipped below the water surface. The bar was supported by a thin stainless steel sheet metal spring and actuated by rapid forward and backward steps of the motor. High quality plane waves were produced. However, drawbacks to the design were observed in the nature of the stepper motor where the actuator moves quickly forward, stops abruptly and then moves quickly backward, stops abruptly and so on. This lead to difficulty in varying the frequency of wave generation. Only a very small range of frequencies produced waves well. Also, the electronic interface to the stepper motor was complicated; it required several digital outputs of a controller system and a third component to interface the motor to the controller.

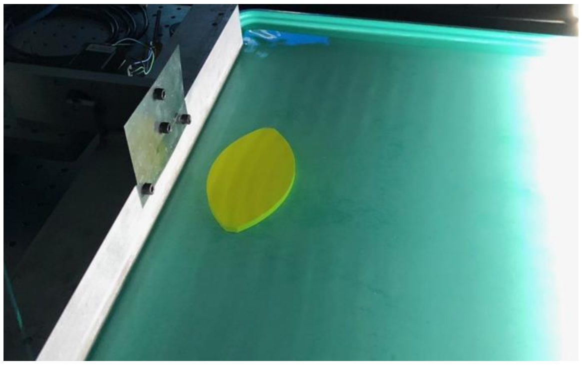


Figure 2. Prototype stepper motor plane wave actuator demonstration with convex lens.

While quality point sources were also made with the stepper motor actuating an arm with a spherical point in the same way (rotating forward and backward in short abrupt steps), a problem was observed in how to deactivate and remove the point sources from the system when they are not needed. The stepper motor could rotate the actuator arm away from the water, but it proved difficult to return the actuator to the same position to re-deploy the wave source.

The voice coil system would be designed from scratch based on a format similar to a mechanical computer hard drive voice coil system. This produces a short arc motion that can be directly applied to a bar for plane waves or to a spherical point to produce a point source. The system to control and interface the voice coil motor is very simple. However, during the prototype phase, the directly attached voice coil system did not have enough power to produce quality plane waves. An intermediate system based on a flexible titanium rod and a linear type voice coil was also tested for plane waves, but its performance was lower than the stepper motor system at this point.

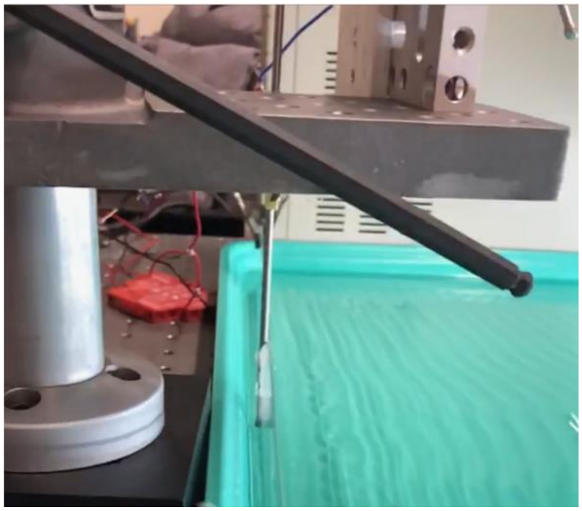


Figure 3. Linear type voice coil plane wave prototype demonstration.

Therefore, early prototypes used a stepper motor controlled, bar system to produce plane waves. In the early stages, development of demonstrations such as placing a double slit structure, or showing the influence of waves passing over a raised lens shape was the primary focus. A good system for point sources remained to be developed.

6. EARLY DEMONSTRATION

After initial development, a working prototype system would be available in a teaching area for class demonstrations and sometimes outreach events such as campus tours. The demonstrations were appropriate, for example, to Optics 101 workshop students in an informal setting. Students or other groups touring the Institute of Optics often enjoyed viewing the early system as an interesting visual demonstration.

Also at this stage, some investigation into the form of illumination to best view the waves took place. Early tests with various illumination methods indicated that a bright uniform white light at an angle very low to the water surface produced the best visual contrast to an observer. This would be important in later designs. A white light led strip was fixed to a bar that lay across the water tray opposite the wave generator. This was an effective illumination source during the early demonstrations of the device and led to the final illumination design during later stages of development.

7. CLASSROOM SYSTEM

With early development complete and having observed the prototype system in use for a substantial period of time, the next phase of the project would be to design a system to be deployable in classrooms and connect to classroom technology systems.

To achieve a platform that could be transported to various classrooms, a system of storing the water, transferring it to the demonstration area, then draining it back down to the storage tank would be necessary. The system and associated water would be large and heavy, and so a medium duty cart with a deep top tray was purchased to take the place of the prototype tray. Since the water depth is very important to the wave motions, a secondary platform would be suspended in the deeper tray with a support system to provide adjustable depth below the water surface. A sixteen gallon holding tank was purchased and attached to the lower platform of the cart. A small pump was mounted near the tank and was connected to a special fitting which fills the upper basin. The pump can be turned on by use of a solid state relay connected to the system controller, and so can be controlled by the computer interface. To drain the water at the end of a demonstration another special fitting was designed and manufactured which connects to the tank below and seals a stopper of a specific height. When water filling the basin reaches the height of the stopper, any additional water will drain back to the tank. This prevents the basin from over filling. To drain the basin entirely, the stopper can be removed.

Figure 4. Specially made drain stopper (black cylinder) prevents over filling of the basin.

The ability to show the wave demonstrations in a classroom setting will require a camera system connected to an onboard computer which a can then be connected to classroom projectors through an HDMI interface. It was decided that a large portion of the budget would be dedicated to a machine vision camera which would add significant functionality and ease of use to the system. A Pixelink® PL-D753CU-AF16 with auto-focusing liquid lens was selected. Multiple aspects of the camera's video acquisition and the liquid lens can be adjusted through the Pixelink Capture® software.

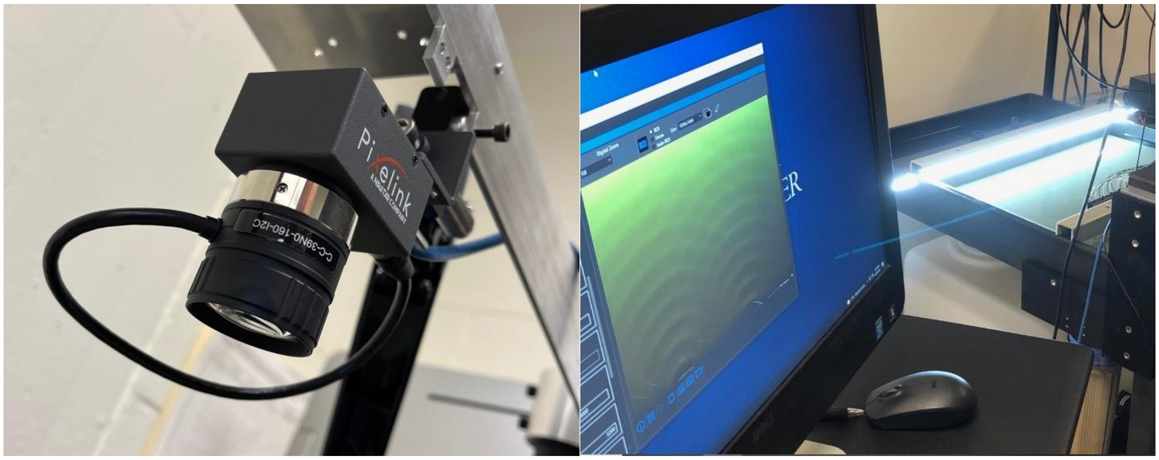


Figure 5. Pixelink camera with liquid lens (left) and video capture with camera system (right).

Most importantly, the camera's acquisition frame rate can be changed to match the wave generating rate which freezes the wave interactions in the video capture. Also, if the frame rate is closely matched, but the camera rate is slightly lower, the wave interactions are slowed. This shows a visual that indicates the waves' travel and interactions at an easy to view pace. An onboard Windows computer is used to run the camera software, run the wave actuator program and provides an HDMI connection to output to classroom technology.

8. ACTUATOR REDESIGN

As the design of the classroom system progressed, a new actuator idea was considered related to array designs. The design appeared promising and would allow some of the advanced wave interactions to be integrated into the system.

The array design would consist of a one dimensional array of individually actuated flexible bars each producing a point source wave. Actuation would be the voice coil type, which would prove more effective here due to the small bar size reducing the requirement for a powerful actuating mechanism. This greatly simplified the control system as well.

Prototypes of this design used handmade electromagnet coils of motor wire pulsed with an electrical signal through a transistor. The electromagnet would periodically pull a strong Neodymium magnet attached to the actuator bar to produce a point source wave. While certain parameters of the coil and electrical pulse influenced the performance, it was found that the most important aspect of this new type of actuator would be the flexibility of the material forming the actuator bar. Several materials were tested including thin brass, stainless steel and aluminum, but the best material was found to be thin plastic shim sheets. This material would also be inexpensive, easy to work with and not suffer from corrosion.

Due to the promising results shown by this new type of actuator and the potential for adding advanced demonstration concepts to the system, it was decided that a sixteen actuator array would be developed to use on the classroom system. Essentially, the array would provide a point source at any of sixteen locations one inch apart. If all of the actuators were activated in phase, then a plane wave would be formed. This also models the diffraction concepts taught in wave optics directly[7].

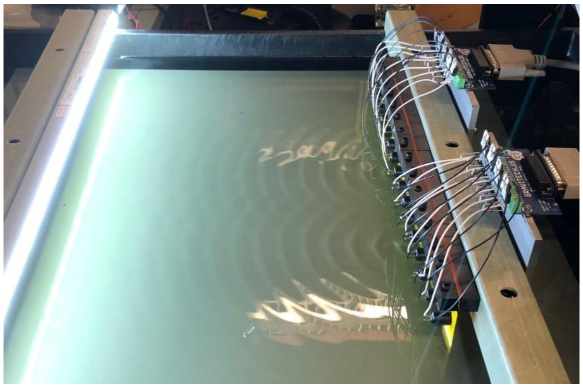


Figure 6. Test of redesigned array type actuator system.

The final design of the array actuator used a single plastic sheet to form the actuator bars with a thin cut between each bar allowing independent motion. The voice coil electromagnet would be attached to each actuator bar using a small 3D printed fitting. The electromagnet would be a ferrite core inductor available to purchase through electronics suppliers. Thin wires would connect the electromagnet to the power handling circuit which consisted of a MOSFET (transistor to turn the electromagnet on with input from the controller) and a Zener diode (to prevent voltage spikes during switching of the circuit) for each of the sixteen actuators. A MOSFET can be directly operated by any digital controller system and provides wave generation using only a single digital output per actuator. The Neodymium magnets in this design were placed perpendicular to the electromagnet coils on adjustment screws giving the ability to correct variation in the strength of each actuator by adjusting the proximity between the electromagnet and the permanent magnet.

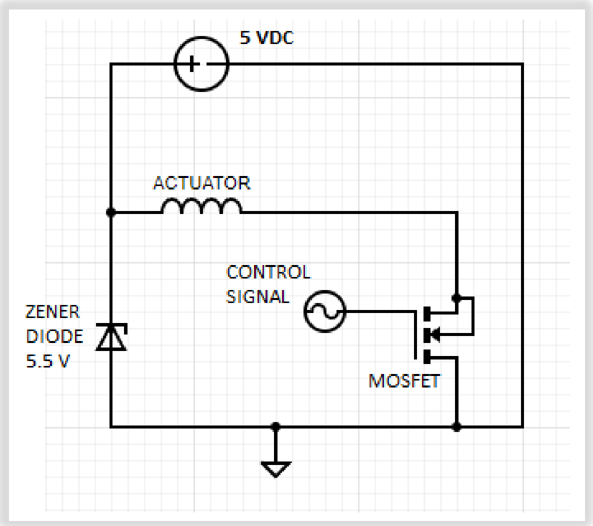


Figure 7. Electrical circuit for a single actuator in the array.

9. INTERFACE AND PROGRAMMING

A major design parameter for the Wave Optics Visualizer is ease of use, and so much attention was given to the development of the user interface. Before selecting a system in which to program the user interface, it was required that a hardware device to integrate the computer operating the user interface program to the actuator power handling circuit be selected.

Several hardware devices were tested to determine the best overall selection for the task. The early prototypes using the stepper motor to drive a bar for plane waves used a Raspberry Pi® microcomputer. This was initially attractive since the Raspberry Pi® could serve as the onboard computer for the whole system, including providing an HDMI video output. However, difficulties were found where additional hardware cards were needed to achieve all of the required outputs to operate the system. These cards proved difficult and unreliable to program and operate.

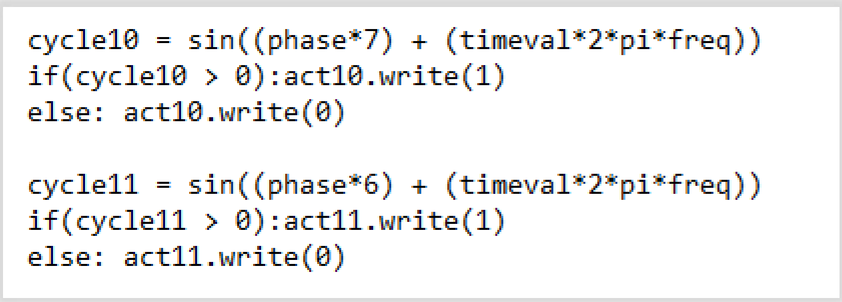
Another device from Raspberry Pi® called the Pico microcontroller was also tested. It is a very simple device and provides all required outputs, but proved difficult to operate in real time with a user interface due to its primary design function being a microcontroller.

Also considered were larger, industrial level digital input/output modules. These were found to be more expensive, had limited functionality and had limited programming tools available.

Finally, two Arduino® microcontroller models had been purchased and used in early prototyping to drive the stepper motor system in various configurations. The Arduino Uno® was considered, but does not provide enough digital output connections. The second model, the Arduino Due®, which was originally purchased to operate the prototype voice coil actuator due to its higher modulation frequency, actually proved to be the best hardware interface for the new, array type actuator design. The model provided enough digital output connections, and a programming add on called Pyfirmata® is available for Python® coding to operate the Arduino Due® in real time through a USB connection.

By the time programming for the classroom system with a graphical user interface was starting, a multitude of wave generating programs for various prototype actuators with various hardware interfaces had already been developed. Therefore significant knowledge of how to generate the repeating inputs that are required to generate waves was available. Three programming methods proved viable. In a microcontroller situation, the program will automatically run in a loop and therefore programming which alters the timing of the loop alters the wave frequency as well. This works well for a system that has a single actuator and does not need to update in real time. The method worked very well for early prototype systems. For systems operated directly from a computer, which is required for real time control of the system, loops can be added to the programming and their timing altered. This is an improvement over the microcontroller programming situation, however presents complications where multiple actuators operate simultaneously and independently.

The ultimate programming solution would prove to be operation of the programming loop relative to an independent clock which accumulates time throughout the running of the program and is non-repetitive. This time value is multiplied by two times Pi and a frequency value input from the user interface. It is then the angle input to a sine operator for each of the sixteen actuators. In this form, a phase value in radians from the user interface is also added to the sine operator input to phase the actuators individually. Now, a condition can be programmed where, for example if the sine operator returns a positive value, the output to that actuator is activated, and if the sine operator value is a negative, the output is deactivated. This results in wave generating oscillations by switching power on and off to the actuator electromagnets at the desired frequency.

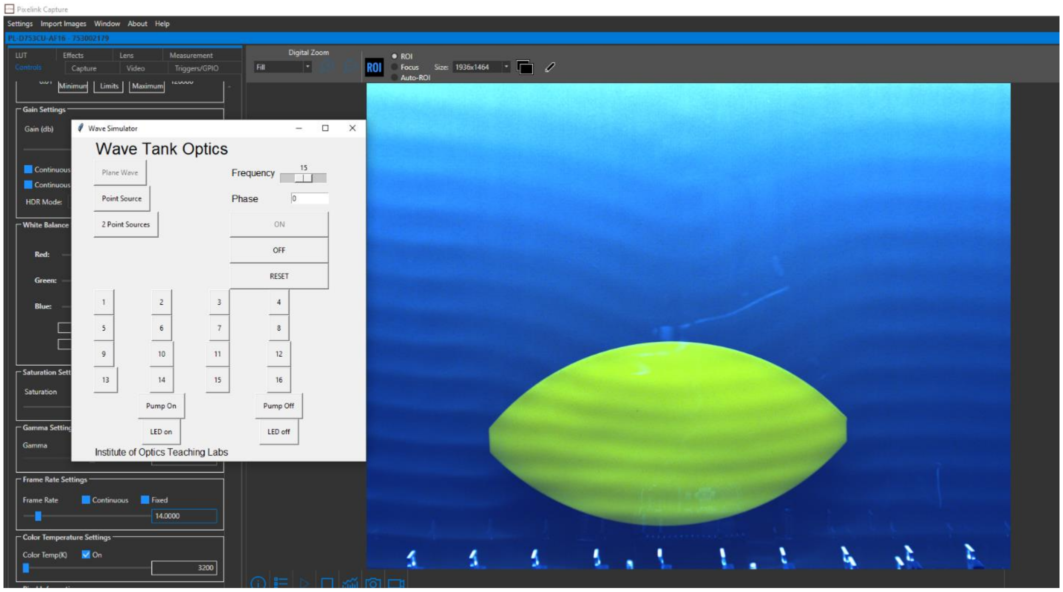


```
cycle10 = sin((phase*7) + (timeval*2*pi*freq))
if(cycle10 > 0):act10.write(1)
else: act10.write(0)

cycle11 = sin((phase*6) + (timeval*2*pi*freq))
if(cycle11 > 0):act11.write(1)
else: act11.write(0)
```

Figure 8. Example Python® code showing wave generating calculation.

General functional modes of the array actuator are also programmed into the user interface. The default mode is a fifteen Hertz plane wave where all of the actuators operate in phase at fifteen Hertz. The frequency can be updated from ten to twenty Hertz in real time, and phase can be added between the actuators, also in real time. Point source mode can be selected where any of the sixteen actuators can be selected to be on. They will all operate at the set frequency, but phase can be added between them in real time. Finally a 'two point source' mode was added which provides a quick way to show two point source interference.



Frequency 15

Phase 0

Frame Rate 14.0000

Color Temp(K) 3200

Size: 1936x1464

Figure 9. Graphical user interface running with video acquisition.

The final functional aspects added to the user interface were the operation of the illumination LED bar and the water pump. Simple on and off buttons were added to the user interface to accomplish these functions.

The user interface remains a very important area for future improvements of the system. Ultimately, integrating the user interface with the camera software is a major goal yet to be accomplished. The Pixelink Capture® software is Python® based and the hope is that a fully integrated user interface with video capture, camera controls and all of the wave generating functions can be accomplished under a single program.

10. ACTUATOR DESIGN REVISION

With the main systems constructed and functioning well, it was determined that a design revision of the wave actuator would take place to attempt to improve overall performance. While the system at this stage did perform very well overall; it was found that the wires connecting the electromagnet coils to the power handling circuit were fragile, difficult to work with and despite being very thin, they did impede the motion of the wave actuating bar significantly. Further, the placement of these connecting wires blocked the view of waves near the actuator. The revision of the wave actuator would rearrange the main components so that the voice coil electromagnets would be fixed and the permanent magnets would be attached to the actuator bar. This would eliminate the wire connections impeding the movement of the actuator bar during wave generation.

The new actuator system would be based on a custom designed and fabricated printed circuit board. The Arduino Due® would be plugged into a set of pin headers soldered to the board. All connections would be made through traces in the board and the necessary power connections, transistors and Zener diodes would be soldered directly to the board. To design the custom printed circuit board, KiCAD® software was used and OSHPark.com® fabricated the design from the design files.

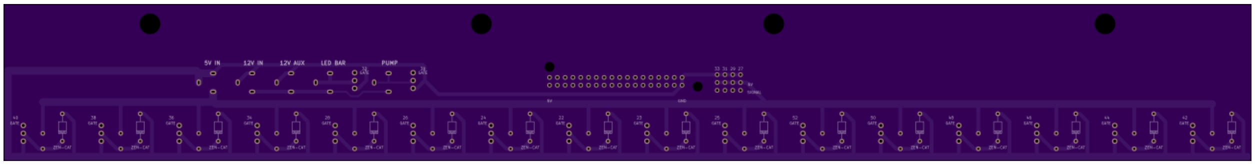


Figure 10. Printed circuit board design file image for revised array type actuator.

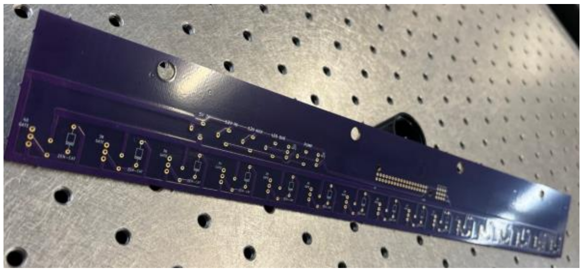


Figure 11. Custom printed circuit board ‘as manufactured.’

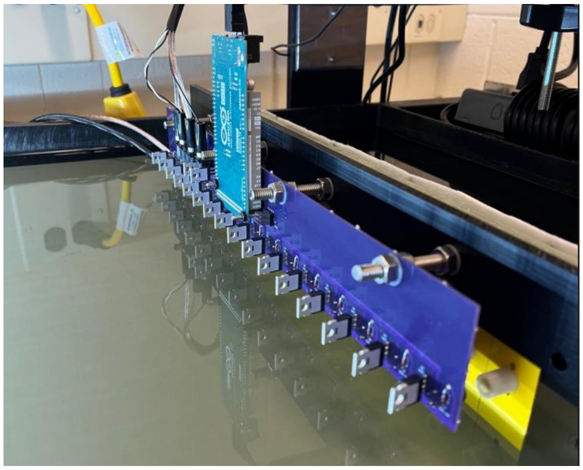


Figure 12. Finalized and installed array type actuator.

This configuration allowed the connection and placement of all components, including those needed to operate the pump and illumination LED system with only one USB connection and four power connections. Overall, it was believed that this effort would lead to a better performing system that would be more reliable, and could be more confidently deployed to classroom settings in the long term.

11. CLASSROOM DEPLOYMENT

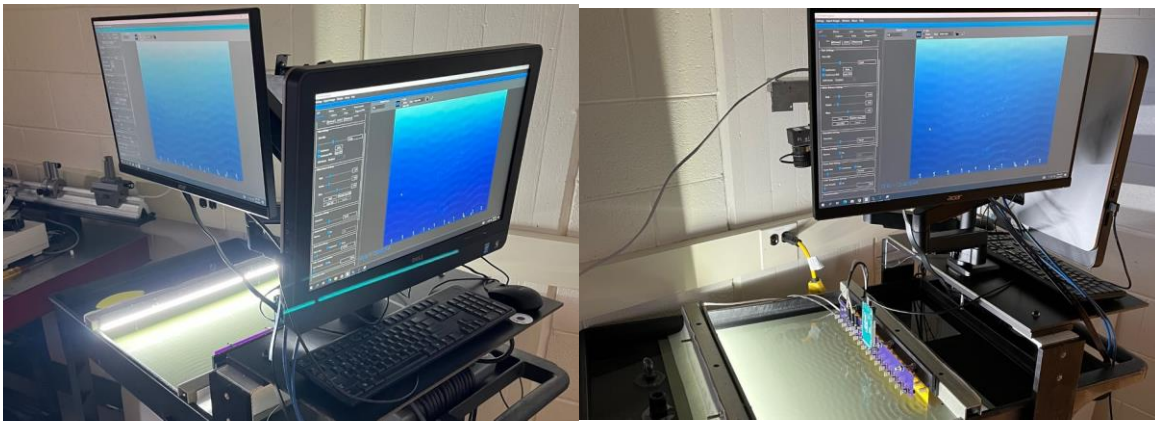


Figure 13. Two views of the complete system in operation.

Until the 2023 Spring semester, the system in its many iterations had provided multiple demonstrations for various tours, campus visits, class workshops and even Photon Camp, which is a week long day camp for local high school students. However, it had not yet been transported from its home location to give a classroom demonstration. The first and so far, the only demonstration in a classroom setting took place April of 2023 when the cart was brought into a lecture hall during Optics 261 (Interference and Diffraction), powered up, water pump activated and the basin filled with water, the on board computer connected by HDMI to the classroom projector system and various wave physics demonstrations were shown to the students on the room projectors and discussed in detail. Once the activities were complete, the basin was then quickly drained, power shut down and disconnected, and the whole system transported out of the classroom with little additional impact on class time.

The first classroom based activity was highly successful from a technical standpoint with no issues setting up the system, connecting to classroom technology or projecting the video capture of the wave physics demonstrations.

Students observed plane waves travelling over a raised convex platform to simulate a lens.

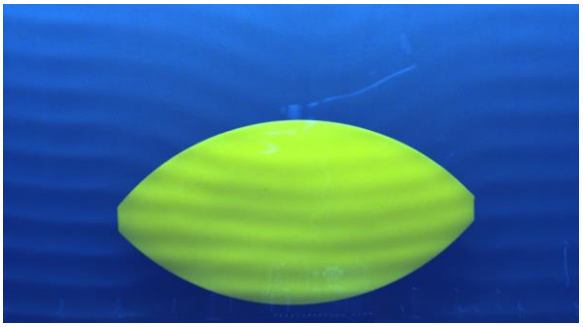


Figure 14. Plane waves over a raised convex platform.

They observed a single point source and then an added second point source to show interference of two coherent point sources. With a discussion of how this also simulates the famous double slit experiment.

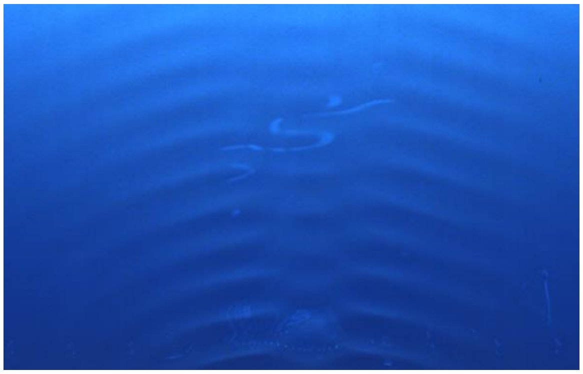


Figure 15. Two closely spaces point sources.

Students also observed multiple evenly spaced point sources, such as every third actuator operating coherently. The similarity to the effect of a diffraction grating was discussed at this time. An adjustment was then made to operate every second point source and students studied the difference in wave patterns.

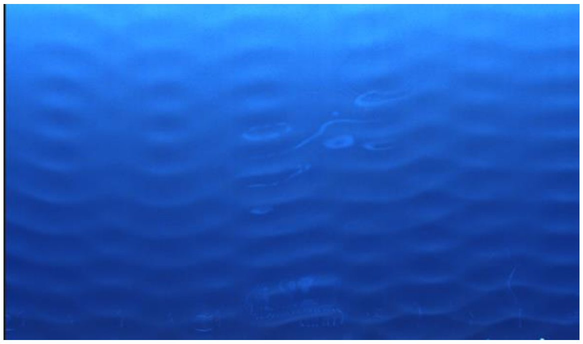


Figure 16. Every second actuator in operation.

Finally, students were given a written activity where they were asked to sketch a set of phasor diagrams, each with one fourth Pi radian phase difference, and to relate this to how phasing each subsequent point source would affect the wave pattern. They were asked to sketch the expected wave pattern before observing it on the Wave Optics Visualizer. The actuators were then set to produce a phased plane wave and a plane wave with a direction not perpendicular to the plane of the actuator was observed.

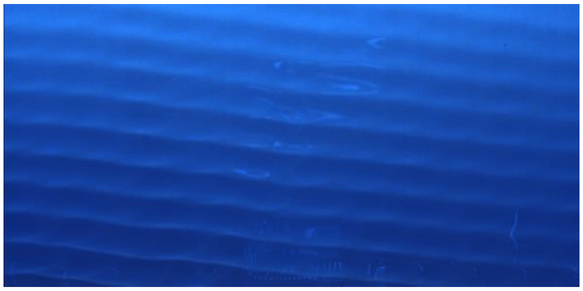


Figure 17. All actuators in operation with one radian of phase between each.

The first classroom use of the Wave Optics Visualizer was very successful and it is expected that, with the system now in a well refined state, use of the Wave Optics Visualizer can be consistently incorporated into various Optics course curricula.

12. CONCLUSION

The project to develop the Wave Optics Visualizer was a comprehensive exercise in research, development, design and construction. Although the system has only recently been completed, the prototype systems that led to the final design provided many interesting and valuable demonstrations to Optics students and diverse visitors to the Institute of Optics at the University of Rochester dating back to Fall of 2021. Important next steps involve a formal method to assess the impact that the Wave Optics Visualizer has on student success in the Institute of Optics curricula, and to further improve and integrate the user interface and video capture system.

ACKNOWLEDGEMENTS

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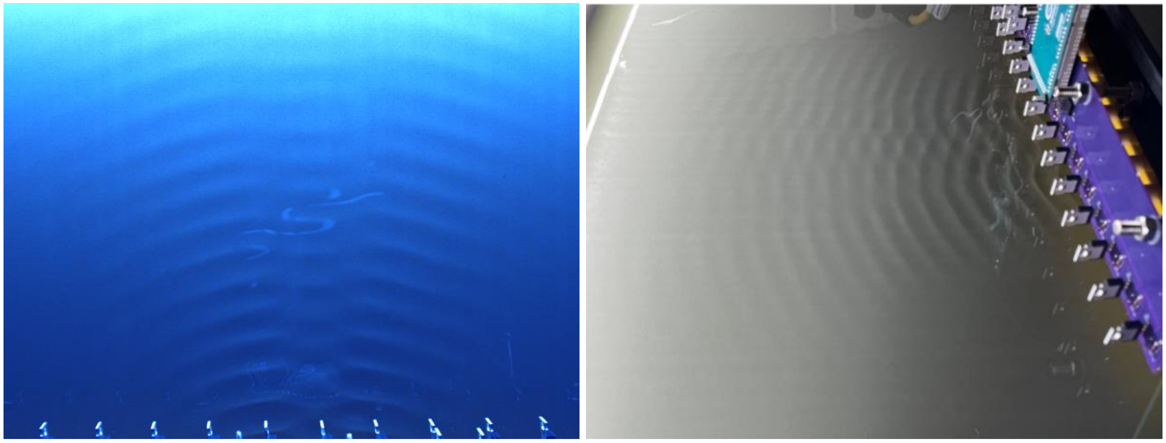
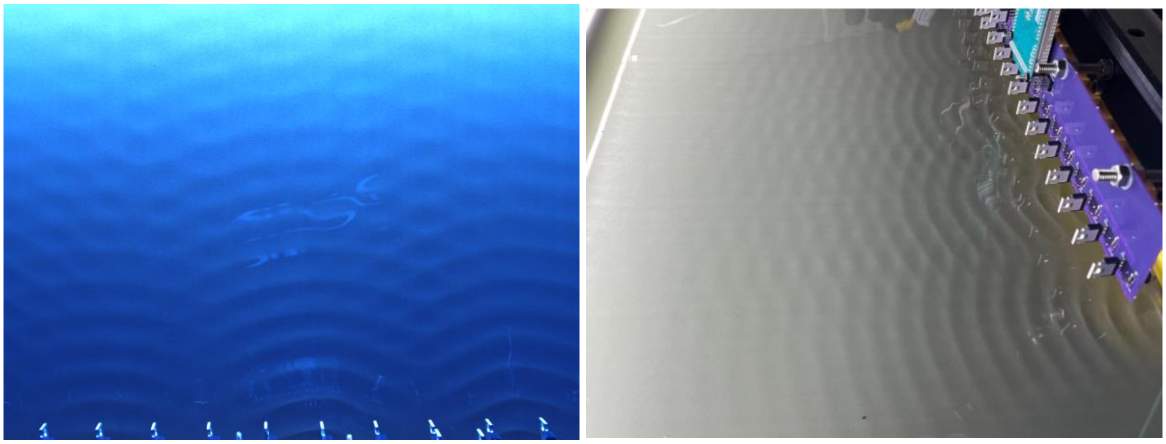
APPENDIX

Wave images

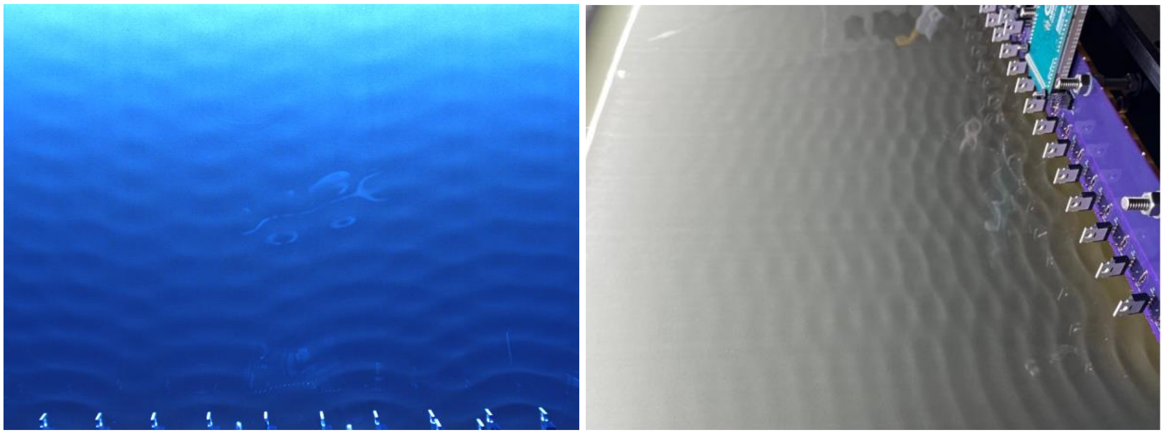
2 point sources



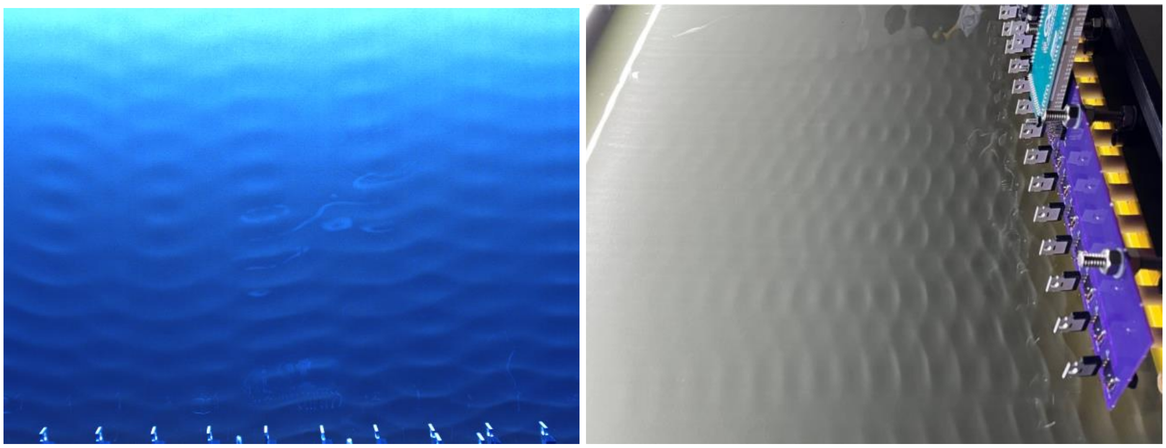
Every fourth actuator



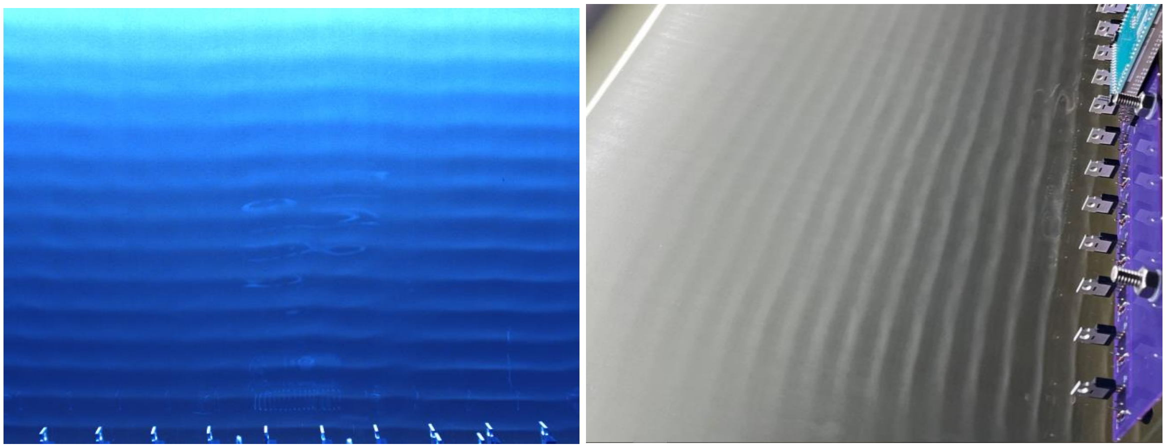
Every third actuator



Every other actuator



Plane wave



Phased (one radian per actuator)