

Submission ID #: 68766

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Project Page Link: https://review.jove.com/files_upload.php?src=20973678

Title: Optically Trapping Large Metallic Particles in Air Using a 'Boat' Trap with Direct-Drawn Sidewalls

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Author Questionnaire

- 1. Microscopy:** Does your protocol require the use of a dissecting or stereomicroscope for performing a complex dissection, microinjection technique, or something similar? **No**
- 2. Software:** Does the part of your protocol being filmed include step-by-step descriptions of software usage? **partial**
- 3. Filming location:** Will the filming need to take place in multiple locations? **no**
- 4. Testimonials (optional):** Would you be open to filming two short testimonial statements **live during your JoVE shoot**? These will **not appear in your JoVE video** but may be used in JoVE's promotional materials. **no**

Current Protocol Length

Number of Steps: 36

Number of Shots: 53

Introduction

Videographer: Obtain headshots for all authors available at the filming location.

Authors: Please note that **the questions will not appear on screen**. Please answer in **stand-alone full sentence with sufficient context**

INTRODUCTION:

~~REQUIRED: Summarize your research focus and the main questions it aims to answer.~~

- 1.1. **Stephen Griffith or Jay Dearden:** Our work describes the construction and operation of a reconfigurable boat-shaped optical trap for capturing and manipulating particles in air.
 - 1.1.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.

~~Describe the research gap or limitation in existing methods and how this protocol addresses them.~~

- 1.2. **Daniel Smalley:** Existing trapping methods compromise between trap localization and capture area; this protocol introduces a boat trap achieving both simultaneously.
 - 1.2.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.

~~Describe the research contexts or systems in which this protocol can be applied.~~

- 1.3. **Daniel Smalley:** This protocol can be applied in standard laboratory environments under ambient air conditions while following class IV laser safety protocols.
 - 1.3.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.

CONCLUSION:

~~What does this protocol allow researchers to study or measure?~~

- 1.4. **Daniel Smalley:** This protocol allows a researcher to draw and quickly modify a boat trap to trap and move a wide variety of particles in the air.

- 1.4.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.

~~How can future studies build on this work? Describe the questions or research directions that can be investigated next.~~

- 1.5. **Daniel Smalley:** Future studies can integrate Field-Programmable Gate Array control to enable programmable manipulation of trap shape, weighting, and cross-sectional location within a 2D plane.

- 1.5.1. INTERVIEW: Named Talent says the statement above in an interview-style shot, looking slightly off-camera.

Videographer: Obtain headshots for all authors available at the filming location.

Protocol

***Videographer:** Please always record an audio slate while filming each shot mentioned in the shotlist.*

2. Optical System Setup for Particle Trapping

Demonstrator: Stephen Griffith

- 2.1. After preparing the carbon-coated glass microsphere, set up the optical system using a kinematic beam elevator and a ruler to set the beam height to 23 centimeters [1].
 - 2.1.1. LAB MEDIA: IMG_4235.MOV: 04:18-04:22
- 2.2. Reduce the laser power to less than 5 milliwatts [1]. Use a polarizer to determine whether the polarization is vertically oriented [2].
 - 2.2.1. LAB MEDIA: rotated.mov: 00:00 – 00:07
 - 2.2.2. LAB MEDIA: polarization1.mov: 00:00-00:11
- 2.3. Adjust the microscope to beam height, facing in the negative z direction, at a distance greater than 100 centimeters from the output of the beam elevator [1].
 - 2.3.1. LAB MEDIA: IMG_4235.MOV: 06:00-06:20
- 2.4. Place a Fourier transform lens 10 centimeters in the negative z direction, with the convex surface facing in the positive z direction [1].
 - 2.4.1. LAB MEDIA: IMG_4235.MOV Timestamps: 11:24 – 11:40
- 2.5. Then, place the remaining 3 Fourier transform lenses 20 centimeters apart, with alternating convexities [1].
 - 2.5.1. LAB MEDIA: IMG_4325.MOV Timestamps: 01:17 – 01:24
- 2.6. Next, position the acousto-optic modulators 10 centimeters in the negative z direction from the lenses closest to and furthest from the laser [1].
 - 2.6.1. LAB MEDIA: IMG_4325.MOV Timestamps: 01:32 – 01:37
- 2.7. Ensure that the acousto-optic modulator closest to the laser is vertically oriented [1].
 - 2.7.1. LAB MEDIA: IMG_4325.MOV Timestamps: 11:07 – 11:17
- 2.8. Position the acousto-optic modulator 2 ten centimeters from the lens furthest from the laser. Align it horizontally and rotate it approximately 2 degrees away from the optical axis [1].
 - 2.8.1. LAB MEDIA: IMG_4325.MOV Timestamps: 02:23 – 02:30
- 2.9. For each channel of the arbitrary waveform generator, connect a voltage-controlled oscillator, an amplifier, and 1 acousto-optic modulator [1]. Then, connect the amplifiers

to the acousto-optic modulators [2].

2.9.1. LAB MEDIA: Figure 5C

2.9.2. LAB MEDIA: IMG_4325.MOV Timestamps: 06:06-06:19, 06:52-06:54

2.10. Using the arbitrary waveform generator, turn the radio frequency signal to both acousto-optic modulators to 175 megahertz [1].

2.10.1. LAB MEDIA: IMG_4325.mov Timestamps: 21:00 – 21:17.

2.11. Then, decrease the tilt of acousto-optic modulator 2 to zero. Gradually increase the angle until the first-order beam reaches its maximum brightness. Confirm that the acousto-optic modulator has returned to approximately the original tilt angle of 2 degrees [1].

2.11.1. LAB MEDIA: IMG_4325.MOV Timestamps: 12:45 – 12:55

2.12. Align both beams exiting the first acousto-optic modulator to enter the second modulator. Of the four exiting beams, allow only the top-right beam to pass through the aperture [1].

2.12.1. LAB MEDIA: IMG_4325.MOV Timestamps: 14:04-14:30

2.13. Next, place a beamsplitter to direct a portion of the beam to an observation surface [1].

2.13.1. LAB MEDIA: IMG_4325.MOV: 17:26-17:40, 18:00-18:03

2.14. With the arbitrary waveform generator amplitudes set to zero, observe the resulting beam at the observation surface appearing as a dot [1].

2.14.1. LAB MEDIA: IMG_4325.mov: Timestamps: 22:36 – 22:50

2.15. Set the vertical channel offset to 3 volts, amplitude to 5 volts, and frequency to 4 kilohertz [1]. Observe the beam forming a vertical line at the observation surface [2].

2.15.1. LAB MEDIA: Figure 7C

2.15.2. LAB MEDIA: IMG_4325.mov Timestamps: 23:00 – 23:30

2.16. Then adjust the horizontal channel offset to 3 volts, the amplitude to 5 volts, and the frequency to 4 kilohertz [1]. The beam should form a diagonal line at the observation surface [2].

2.16.1. LAB MEDIA: Figure 7E

2.16.2. LAB MEDIA: IMG_4325.mov Timestamps: 23:40 – 23:50

2.17. Tune the vertical channel to 8 kilohertz and a 90-degree phase offset [1], resulting in a Lissajous pattern on the observation surface [2].

2.17.1. LAB MEDIA: Figure 7G

2.17.2. LAB MEDIA: IMG_4325.mov Timestamps: 24:39 – 24:45

- 2.18. Then, press the **Align Phase** button to convert the Lissajous pattern to a parabolic shape [1]. Adjust the vertical channel phase offset to refine the parabolic shape [2] and observe the refined parabolic pattern at the observation surface [3].

2.18.1. LAB MEDIA: Figure 7I and IMG_4325.mov Timestamps: 24:45 – 24:50

2.18.2. LAB MEDIA: Figure 7K

2.18.3. LAB MEDIA: IMG_4325.mov: 24:48-24:58.

3. Imaging System Setup and Particle Trapping Procedure

- 3.1. Place a telecentric lens with a 45 millimeter focal length on a linear stage, positioning it 55 millimeters in front of the objective in the positive z direction [1]. Then, place a dichroic filter designed to reflect 532 nanometer light in front of the lens [2].

3.1.1. LAB MEDIA: IMG_4348.mov: 00:26-00:30

3.1.2. LAB MEDIA: IMG_4348.mov: 04:29-04:44

- 3.2. Connect the camera to a personal computer using a universal serial bus cable with the associated imaging software [1].

3.2.1. LAB MEDIA: IMG_4348.mov: 01:29-01:32

- 3.3. Then, tilt the dichroic filter slightly between 5 and 10 degrees until the parabolic trap shape appears [1].

3.3.1. LAB MEDIA: IMG_4348.mov: 04:56-05:14

- 3.4. Illuminate the beamsplitter with a fiber light source [1] and adjust the fiber light to center its illumination around the parabolic trap [2].

3.4.1. LAB MEDIA: IMG_4362.mov: 00:15-00:25

3.4.2. LAB MEDIA: light.mp4

- 3.5. Using a laboratory spatula, place approximately 1 gram of particles inside a 25 millimeter long, 12 millimeter diameter glass cylinder mounted to allow rotation along the cylinder axis [1].

3.5.1. LAB MEDIA: insertion.MOV

- 3.6. Place the loaded glass cylinder centered at 15 millimeters away from the objective, corresponding to the objective working distance [1].

3.6.1. LAB MEDIA: IMG_4362.mov: 01:39-01:47

- 3.7. After rotating and tapping the cylinder, observe the camera display showing default or no trapped particles [1], particles falling [2], and trapped particles [3].

3.7.1. LAB MEDIA: tap.avi: 00:00-00:05

3.7.2. LAB MEDIA: tap.avi: 02:58-03:03

3.7.3. LAB MEDIA: tap.avi: 03:37-03:39

4. Computational Tracking with OpenCV

4.1. After installing and configuring the software, launch Visual Studio 2022 and open the project file [1]. Press the green **Run** button to start the program. Observe the video feed and terminal appearing on the screen [2].

4.1.1. SCREEN: ScreenRecording1.MP4: 00:00-00:09

4.1.2. SCREEN: ScreenRecording1.MP4: 00:09-00:15

4.2. Ensure that the green trapping parabola is visible on the video feed. If it is not visible, adjust power, filtering, or alignment until the trapping region appears [1].

4.2.1. SCREEN: IMG_4348.MOV Timestamps: 04:56 – 05:14

4.3. Press the Windows, Shift, and S key simultaneously to capture the screen [1]. Click and drag the mouse pointer from the top left to the bottom right corner of the video feed [2]. Click the pop-up to open the screenshot editor [3]. Click the **Edit in MS Paint** button within the editor [4].

4.3.1. SCREEN: ScreenRecording1.mp4: 00:17-00:19,

4.3.2. SCREEN: ScreenRecording1.mp4: 00:20-00:25

4.3.3. SCREEN: ScreenRecording1.mp4: 00:26-00:29

4.3.4. SCREEN: ScreenRecording1.mp4: 00:29-00:33

4.4. Then, place the cursor in the top left corner of the parabola in the MS Paint window [1]. Record the coordinates shown at the bottom left corner as xmin (*X-Minimum*) and ymin (*y-Minimum*) [2].

4.4.1. SCREEN: ScreenRecording1.mp4: 00:35-00:42.

4.4.2. SCREEN: ScreenRecording1.mp4: 01:01 and 01:19-01:20. *Video editor: Highlight the values displayed at the bottom left corner of the window*

4.5. Once done, close the video feed by pressing the Escape key [1].

4.5.1. SCREEN: ScreenRecording1.mp4: 01:27-01:28

4.6. Enter xmin, xmax, ymin, and ymax on line 280 in the is_trapped (*Is-Underscore-Trapped*) function of main.cpp (*Main-C-P-P*) within the project [1].

4.6.1. SCREEN: CalibrationR2.mp4: 01:10-01:35

4.7. For frequency selection, launch Visual Studio 2022 and open the project file if it is not already open [1].

4.7.1. SCREEN: ScreenRecording1.MP4: 00:06 – 00:09

4.8. Open Windows PowerShell or Command Prompt. Run the command `python -c import`

random and print a random sample from the range 0 to 101. Then, copy the generated list of test numbers [1].

4.8.1. SCREEN: GetRandomNumbers.mp4: 00:00 –00:11

4.9. Edit line 443 of main.cpp by pasting the generated list into the test numbers sequence [1] and save the project in Visual Studio 2022 [1].

4.9.1. SCREEN: EditingR1.mp4: 03:30-03:40

4.9.2. SCREEN: ReplacseAndSaveRandomNumbers.mp4: 00:10 –00:13

4.10. Increase laser power to the level needed for the experiment and open the results.txt file in a text editor. Observe that each program run generates new results under the heading Start of a new batch of results in the format test number result, followed by trap time in nanoseconds [1].

4.10.1. SCREEN: EditingR1.mp4: 05:37-06:04

4.11. For data visualization, copy the test numbers and trap times from the comma-separated values file into example.xlsx. After applying the required filters, observe the additional columns and a scatter plot that populates with trap time versus trap draw frequency [1].

4.11.1. SCREEN: EditingR1.mp4: 9:17-9:28

Results

5. Results

- 5.1. Carbon-coated microspheres produced dark shadows when backlit [1].
 - 5.1.1. LAB MEDIA: Figure 9E,F. *Video editor: Highlight the dark particle shadows on the pale background*
- 5.2. Glass microsphere particles with dimensions on the order of 100 micrometers settled approximately to the bottom of the parabolic trap with a slight bias toward the direction of scan [1].
 - 5.2.1. LAB MEDIA: Figure 9F. *Video editor: Highlight the green curved trap area with the dark particle shadows near its lower edge*
- 5.3. When a particle was successfully trapped, the automated particle detection software displayed a red “T” [1]. When no trapped particle was found, the software displayed a green “N” [2].
 - 5.3.1. LAB MEDIA: Figure 12A. *Video editor: Highlight the red “T” label*
 - 5.3.2. LAB MEDIA: Figure 12B. *Video editor: Highlight the green “N” label*
- 5.4. Trapping rates and lifetimes may increase or decrease as a function of environmental variables such as temperature or humidity [1].
 - 5.4.1. LAB MEDIA: Figure 13A–C.
- 5.5. Solid gold particles on the order of 1 micrometer were not observable along the optical axis, but their light scatter was observed orthogonal to the axis [1].
 - 5.5.1. LAB MEDIA: Figure 14C–E.
- 5.6. Video recordings confirmed that particles maintained their position for extended durations exceeding several minutes [1].
 - 5.6.1. LAB MEDIA: Figure 14C–E. *Video editor: Highlight the circled trap point in each frame*

1. Microsphere

Pronunciation link: <https://www.merriam-webster.com/dictionary/microsphere>

IPA: /'maɪkrəˌsfɪr/

Phonetic Spelling: my·kruh·sfeer

2. Kinematic
Pronunciation link: <https://www.merriam-webster.com/dictionary/kinematic>
IPA: /ˌkɪnəˈmætɪk/
Phonetic Spelling: kin·uh·mat·ik
3. Polarizer
Pronunciation link: <https://www.merriam-webster.com/dictionary/polarizer>
IPA: /ˈpəʊləˌraɪzər/
Phonetic Spelling: poh·luh·ry·zur
4. Polarization
Pronunciation link: <https://www.merriam-webster.com/dictionary/polarization>
IPA: /ˌpəʊlərəˈzeɪʃən/
Phonetic Spelling: poh·luh·ruh·zay·shuhn
5. Fourier
Pronunciation link: <https://www.merriam-webster.com/dictionary/Fourier>
IPA: /ˈfɔəri/, /ˈfɔriər/
Phonetic Spelling: foor·ee·ay; foor·ee·ur
6. Convexities
Pronunciation link: <https://www.howtopronounce.com/convexities>
IPA: /kənˈvɛksətɪz/
Phonetic Spelling: kuhn·vek·suh·teez
7. Acousto-optic
Pronunciation link: <https://www.howtopronounce.com/acousto-optic>
IPA: /əˌkuːstəʊ ˈɑːptɪk/
Phonetic Spelling: uh·koos·toh op·tik
8. Modulator
Pronunciation link: <https://www.merriam-webster.com/dictionary/modulator>
IPA: /ˈmɔːdjəˌleɪtər/
Phonetic Spelling: mod·yuh·lay·tur
9. Arbitrary
Pronunciation link: <https://www.merriam-webster.com/dictionary/arbitrary>
IPA: /ˈɑːrbəˌtrəri/
Phonetic Spelling: ar·buh·trair·ee
10. Waveform
Pronunciation link: <https://www.merriam-webster.com/dictionary/waveform>
IPA: /ˈweɪvˌfɔːrm/
Phonetic Spelling: wayv·form
11. Oscillator
Pronunciation link: <https://www.merriam-webster.com/dictionary/oscillator>
IPA: /ˈɑːsəˌleɪtər/
Phonetic Spelling: os·uh·lay·tur
12. Amplifier
Pronunciation link: <https://www.merriam-webster.com/dictionary/amplifier>
IPA: /ˈæmpləˌfaɪər/
Phonetic Spelling: am·pluh·fy·ur

13. Megahertz
 Pronunciation link: <https://www.merriam-webster.com/dictionary/megahertz>
 IPA: /'megə,hɜ:ts/
 Phonetic Spelling: meg·uh·hurts
14. Aperture
 Pronunciation link: <https://www.merriam-webster.com/dictionary/aperture>
 IPA: /'æpər,tʃər/
 Phonetic Spelling: ap·ur·chur
15. Beamsplitter
 Pronunciation link: <https://www.howtopronounce.com/beamsplitter>
 IPA: /'bi:m,splitər/
 Phonetic Spelling: beem·split·ur
16. Lissajous
 Pronunciation link: <https://www.howtopronounce.com/lissajous>
 IPA: /'li:sɑ:ʒu:/
 Phonetic Spelling: lee·sah·zhoo
17. Parabolic
 Pronunciation link: <https://www.merriam-webster.com/dictionary/parabolic>
 IPA: /,perə'bɑ:lɪk/
 Phonetic Spelling: pair·uh·bol·ik
18. Telecentric
 Pronunciation link: <https://www.howtopronounce.com/telecentric>
 IPA: /,teli'sentrik/
 Phonetic Spelling: tel·ee·sen·trik
19. Dichroic
 Pronunciation link: <https://www.howtopronounce.com/dichroic>
 IPA: /dar'kroʊɪk/
 Phonetic Spelling: dye·kroh·ik
20. Universal Serial Bus
 Pronunciation link: <https://www.merriam-webster.com/dictionary/universal>
 IPA: /,ju:nə'vɜ:səl 'sɪriəl bʌs/
 Phonetic Spelling: yoo·nuh·vur·suhl seer·ee·uhl bus
21. Objective
 Pronunciation link: <https://www.merriam-webster.com/dictionary/objective>
 IPA: /əb'dʒektɪv/
 Phonetic Spelling: ub·jek·tiv
22. Spatula
 Pronunciation link: <https://www.merriam-webster.com/dictionary/spatula>
 IPA: /'spætʃələ/
 Phonetic Spelling: spach·uh·luh
23. OpenCV
 Pronunciation link: No confirmed link found
 IPA: /'oʊpən si:vi:/
 Phonetic Spelling: oh·puhn see·vee

24. Simultaneously

Pronunciation link: <https://www.merriam-webster.com/dictionary/simultaneously>

IPA: /,sɪməl'teɪniəsli/

Phonetic Spelling: sy·muhl·tay·nee·uhs·lee

25. Nanoseconds

Pronunciation link: <https://www.merriam-webster.com/dictionary/nanosecond>

IPA: /'nænəˌsekənd/

Phonetic Spelling: nan·uh·sek·uhnd