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Development of an Optical Tweezers Demonstration

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Abstract. Optical tweezers are important tools that are used in several scientific fields. An optical tweezers demonstration was developed by testing several different lasers, particles, and particle environments. The final product was a semienclosed 3D-printed casing with a sooted base plate. This demonstration picked up soot particles using a 250-mW 650-nm laser coupled to a 29-mm diopter focusing lens by Edmund Optics [1].

INTRODUCTION

Optical tweezers are important tools that use a converging laser beam to trap particles at the beam's focal point. To promote STEM and, more specifically, laser physics, an optical tweezers demonstration kit for Society of Physics Students (SPS) outreach events has been developed.

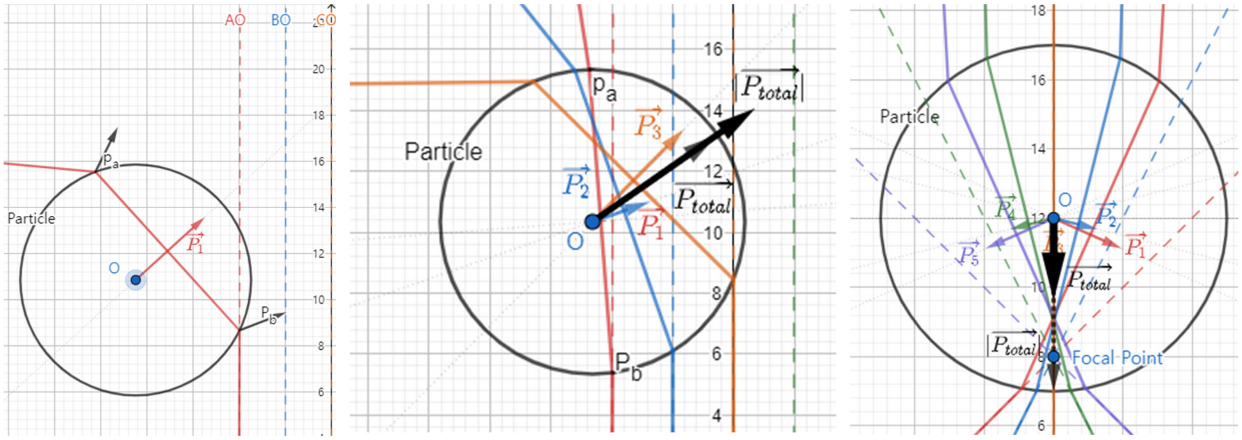
The goals of the development project were as follows:

- **Safe.** As the minimum hold power required for an optical tweezers laser is 24 mW [1] and the lasers used for this project were 200 mW (for a 650-nm beam), safe handling of the beam and a beam dump were needed. Also, trapped particles are nanosized and can become an irritant as an aerosol. An enclosed container or special environment for the particles was needed.
- **Inexpensive.** Most optical tweezer experiments are \$2000–\$5000 [2], but when used only for demonstrations, a high-grade experiment kit is not needed. Creating a kit for less than \$100 that includes optics by Edmund Optics [3] was desired.
- **Easy, consistent, and repeatable.** The objective of this demonstration was to show that particles were being trapped and followed the laser's focal point. We needed a high rate of successful trapping of the particles.
- **Easy to understand.** Practical and accessible explanation materials were needed. For this demonstration, we used optical simulations with conservation of momentum in GeoGebra [4].

To achieve these goals, we tested different kinds of particles, different lasers and coupled lenses, and different positioning (to find the perfect focal point). We also looked at different visual learning materials to help students understand the theory behind optical tweezers. The most recent iteration of our demonstration and our project files can be seen and recreated on Project Evolution in a GitHub repository [5].

Optical Tweezers Theory

The basic theory behind optical tweezers can be explained with conservation of momentum. When the ray of a beam is incident on a dielectric particle, it refracts inside the particle [6] as in Fig. 1(a). As the direction of the ray changes due to refraction, the momentum of the ray also changes. Due to the conservation of momentum, radiant pressure at the surface of the particle, shown as p_a and p_b in Fig. 1(a), is applied. The total pressure, $\boldsymbol{p_1}$, applied to the particle causes an acceleration toward the center of the beam. When using a TEM-00 mode beam, the ray in the center of the beam is strongest and it is cylindrically or azimuthally symmetric around the axis of the beam at *CO*. The restoring force, $\boldsymbol{p_1}$, causes the particle to stay in the axis of the beam as in Fig. 1(b). However, the rays of the beam will keep accelerating the particle in the direction of the beam, so a parallel beam is not suitable for optical tweezers [4].



(a) (b) (c)

FIGURE 1. GeoGebra simulation with parallel rays (the beam direction is up) and a particle. (a) When the particle is incident with the outer rays of the beam, the rays are refracted. This results in a change of momentum at the first and second refraction, shown as p_a and p_b, respectively, and a net force shown as $\vec{P}_1$. (b) When the particle is inside the beam, the applied net force on the particle is shown as $\overrightarrow{p_{total}}$. Its unit vector, with a length of the radius of the particle, is $|\overrightarrow{p_{total}}|$. (c) When the particle is beyond the focal point of the beam, there is some range where the direction of the net force applied to the particle is against the direction of the beam.

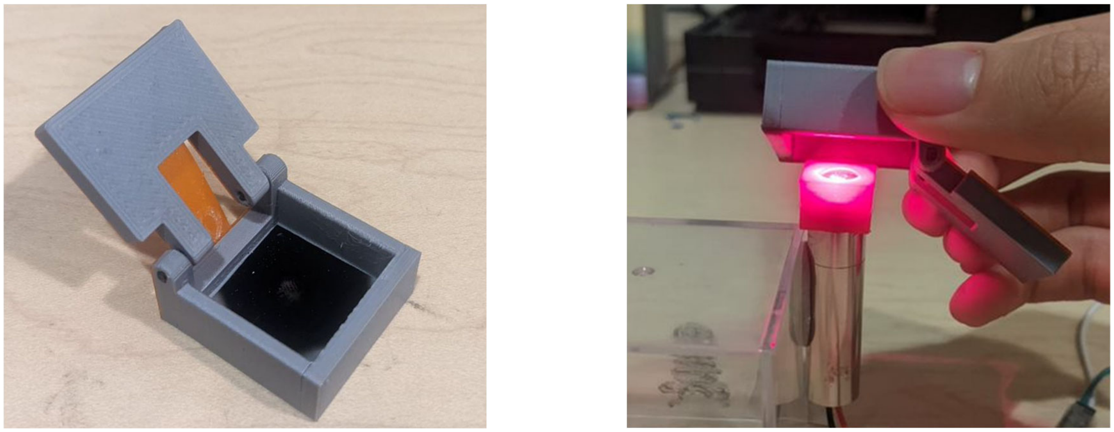
As shown in the images of Fig. 1, any displacement from the center of the laser beam will result in a restoring force back to equilibrium. Any particle within the restoring range of the beam is trapped at the equilibrium point, where the focal point is.

DEMONSTRATION

To begin the demonstration, the theory behind optical tweezers is explained. We used the GeoGebra optical tweezers simulation to show that particles in a parallel beam feel pressure to move toward the beam axis, and the particles in the focused beam stay at the focal point.

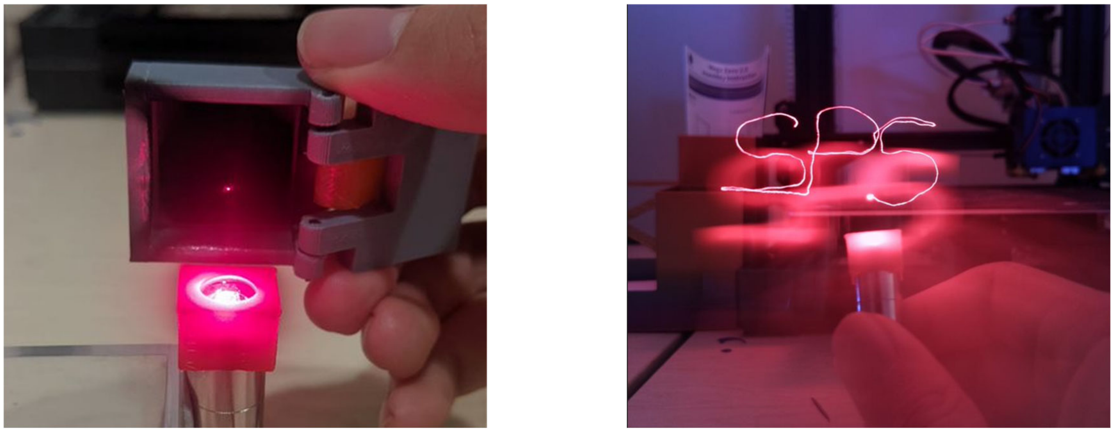
Then the physical demonstration starts. Five designs were tested and can be found in the GitHub repository [5]. This paper introduces the latest design, with improved designs located in the GitHub repository. A nominally 250-mW, 650-nm, class-III B laser was used, and all safety guidelines from the Occupational Safety and Health Administration [7] were followed. As the beam was focused with a high focal angle, rays beyond 5 cm from the focal point were weak enough to be considered safe. The particles came from soot on a glass cover slip; however, any surface where soot can be placed works. A lens with a diameter of 9 mm and focal length of 27 mm was used. The rail for the laser and the lens was 3D printed as one piece to secure both the lens and the laser, as shown in Fig. 2(b), and to ensure safety by inhibiting a concentrated reflected beam. The sooted glass was secured with a 3D-printed container as shown in Fig. 2(a).

We start with the sooted glass container close to the laser aperture, as shown in Fig. 2(b). Slowly we move the sooted container away from the laser and pass the sooted surface through the focal point. As the sooted glass passes through the particle trapping zone, an ~1.5-μm soot particle is removed and trapped as shown in Fig. 3(a). When properly focused, the laser was strong enough to trap the particles in air, and we could move the laser without dropping the particles. We demonstrated the strength of the particle tweezers by writing "SPS" in the air with a long exposure camera, as shown in Fig. 3(b). The associated videos in the GitHub repository show the actual demonstration [5].



(a) (b)

FIGURE 2. Diagram of the setup: (a) 3D-printed container with a sooted glass plate inside, and (b) particle being removed from the sooted surface. See GitHub repository for improved designs.



(a) (b)

FIGURE 3. (a) Trapped particle. (b) The particle was moved/accelerated to spell "SPS" during a long exposure image.

CONCLUSION

With this project we introduced the theory behind optical tweezers using GeoGebra simulations and created a demonstration kit for less than $100, meeting our initial goals. In the future we will write a detailed manual that SPS chapters at other schools can use to create optical tweezers and demonstrate this phenomenon.

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