Optical force model based on sequential ray tracing

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We discuss how information available from ray-tracing techniques can be used to calculate optical forces and torques on particles. A general ray-trace computer code is augmented with the polarization and irradiance distributions of the illumination and Fresnel surface coefficients to give a reasonably accurate prediction of interaction with large particles out of the focal plane. Calculations of trapping location versus nonuniform illumination conditions are compared with an experiment. Other example calculations include trapping a hemispherical lens and a two-particle trap.

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1. Introduction

Following the advances in computing speed and increased memory, ray-tracing software such as Zemax and Code V has become increasingly powerful [1,2]. This performance improvement has allowed the modeling of extremely complicated systems. By coupling an optical force model with a ray-trace code, simulation of optical forces associated with sophisticated systems can be implemented in a straightforward manner.

In Section 2 we give a brief background of the methods used to model optical force and their applications. In Section 3, a sequential ray-trace optical force simulation is described in detail. In Section 4, results from an experiment are used to verify the simulation. Section 5 illustrates examples showing the flexibility of ray-trace modeling applied to optical force calculation. Conclusions are listed in Section 6.

2. Background

When light interacts with matter it can be reflected, refracted, absorbed, or any combination of these possibilities. These interactions cause a change in the direction of the energy (momentum) of the light. Thus, due to conservation of energy, an equal and opposite momentum (force) is transferred to the matter that interacts with the light. By properly balancing all of the forces that occur everywhere on a particle in the vicinity of a focused laser beam, an optical trap (laser tweezers) can be created [3,4].

Motion due to gradient and scattering forces on micrometer-sized particles was demonstrated by Ashkin [3] at Bell Labs in 1970. The forces can be modeled using a ray-based model, an electromagnetic model, or a hybrid of the two. The ray model, which Ashkin used, approximates the propagation of light with a collection of rays that are normal to the wavefront [4]. The interaction of a ray with the surface of a particle gives the force $\mathbf{f}$ transferred from the ray to the particle, as shown in Fig. 1. By taking a summation of the forces from all rays, the total force $\mathbf{F}_O$ on a particle is calculated. This model becomes inaccurate when the wavelength of light approaches the size of the particle. The ray model also fails to predict some effects, such as the torque transferred from a circularly polarized beam to a birefringent particle and resonant frequencies inside a particle.

The optical forces can also be modeled using an electromagnetic description, which is appropriate for all particle sizes. In this case, the electromagnetic field distribution is first calculated at some plane in

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