

Proposed Mechanisms of Optical rotors

Single Molecule: Final Report submission by Travis Hoppe

Optical tweezers, along with other single molecule methods, have found incredible versatility in the study of biological systems. This paper proposes their use to create an optical rotor using two intersecting perpendicular laser traps, and expounds on various applications.

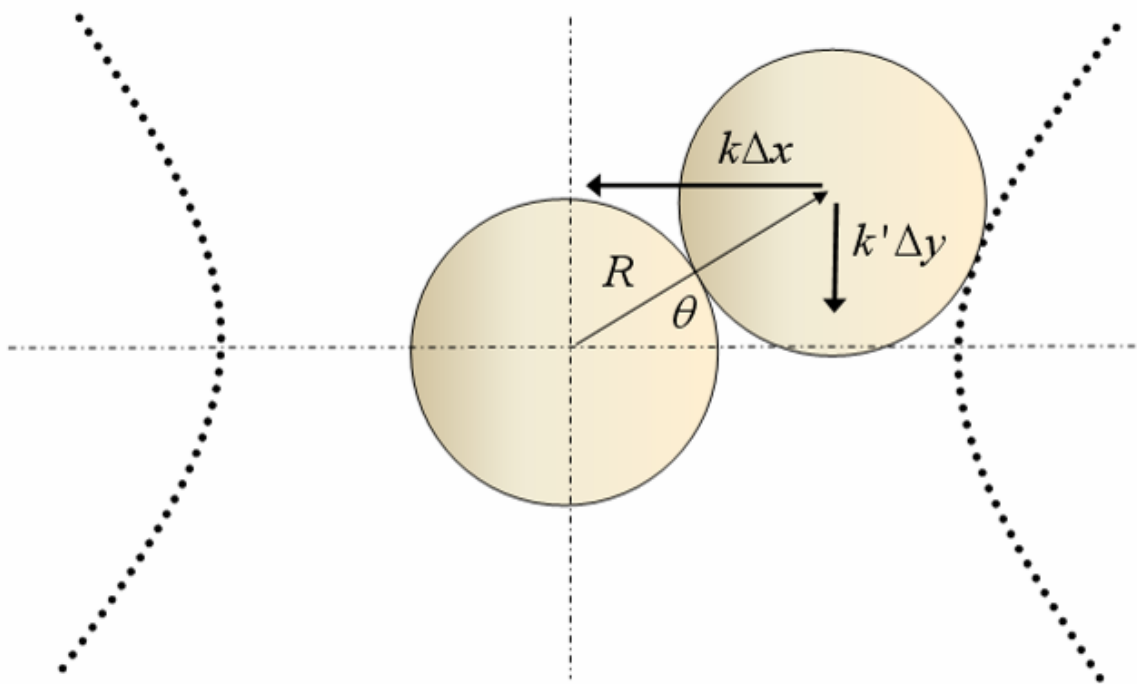
Optical tweezers use a focused laser beam to exert photonic pressure on an object. Light diverges along its path of the beam due to its characteristic dispersion. An object small enough to be inside this path feels a three dimensional pressure gradient, due to the non-uniformity of the intensity across the dispersion. The profile, usually modeled with a Gaussian distribution, will create a net force on the object if it is not perfectly aligned in the optical trap. This force acts as a restoring force towards the center of the intensity of the beam. It has been shown that it is a reasonable approximation to model this force as Hooke's law for short distances:

$$F = -k\Delta x$$

Where k is a parameter dependent on several factors such as the ratio of the refraction index of the material and the medium, the numerical aperture of the lens and the intensity of the beam. In a real physical system, the laser contributes not only refraction (the gradient force) but also a scattering force due to light reflection. This results in a shifted equilibrium position. Quantitatively this changes the results of the analysis of this paper, but *qualitatively* the system behaves the same. Most laser are harmful to biological system but the wavelength of the beam can be chosen by the experimenter to correspond to poor absorption rates of the biological systems being studied. Usually an infrared wavelength of $\lambda = 1064\text{nm}$ is sufficient for this purpose.

In this proposed experimental setup, we are not asking any specific biological question *per se*, rather we seek to construct a device that enables manipulation of biological samples in a (presumably) novel way. Each phase of the experimental design is an extension of the previous one, and as such, a more radical idea of single molecule manipulation. The edifice then rests on this the presumption that the initial device functions as stated.

A solution is prepared consisting of many beads with dielectric properties and a radius of $1\mu\text{m}$ (a standard size, see[1]). The sample is prepared in a vacuum, or enough such that effect due to Brownian motion can be discarded. Then, two beads are attracted so that they rotate as one rigid body. This can be done in any manner of ways, so as long as the bead contact remains fixed and is much greater than the strength of the beam. After capturing the bead-bead particle, we observe the forces acting on the beam. Notice in the schematic show below, unless the rotation of the bead is a multiple of 90 degrees, there will be an external torque on the beads.



Writing down the kinematics of the system (with equal masses and radii, r) we see that the inner bead, by virtue of being centered, experiences no torque. For the outer bead (with $R=2r$) we have:

$$\sum \tau = I\alpha$$

$$R \times F_1 + R \times F_2 = (I_{inner} + I_{outer})\alpha$$

$$R(k\Delta x \cos \theta) - R(k' \Delta y \sin \theta) = (\frac{2}{5}mr^2 + mR^2 + \frac{2}{5}mr^2)\alpha$$

$$R(k(R \sin \theta) \cos \theta - k'(R \cos \theta) \sin \theta) = \frac{21}{5}mR^2\alpha$$

$$\frac{5(k - k')}{21m} \sin \theta \cos \theta = \gamma \sin \theta \cos \theta = \alpha$$

Where γ is clearly a constant related to the parameters of the beam. The maximum torque is clearly at 45° , but at zero when parallel to either axis since either the force or the cross product vanishes. If $k \neq k$, as in the case of a beam exhibiting spatial polarity, then the beads will rotate once displaced from the axis. The magnitude of the acceleration can be plotted as a function of theta. Clearly the system will oscillate as if it were contained in a harmonic oscillator potential [Figure 1].

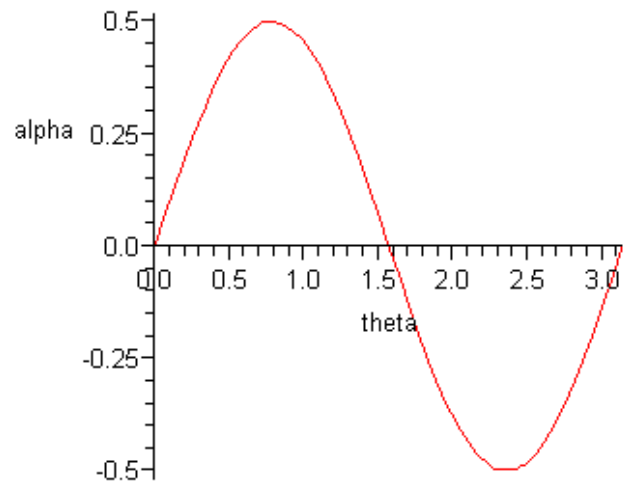


Figure 1 - Angular acc. with one laser

If however, we have two beams intersecting at right angles, we can adjust the intensity of the beam such that the angular acceleration is always positive. Let the first beam lie parallel to the x-axis and the second beam perpendicular to it with our beads somewhere in the first quadrant. As the first beam turns on it will rotate the beads until they reach the second quadrant. As soon as this happens shut off the first beam and turn on the second one. The angular acceleration now will look like [Figure 2].

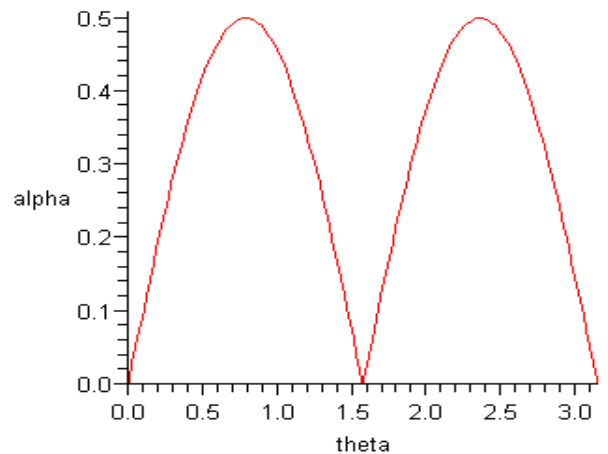
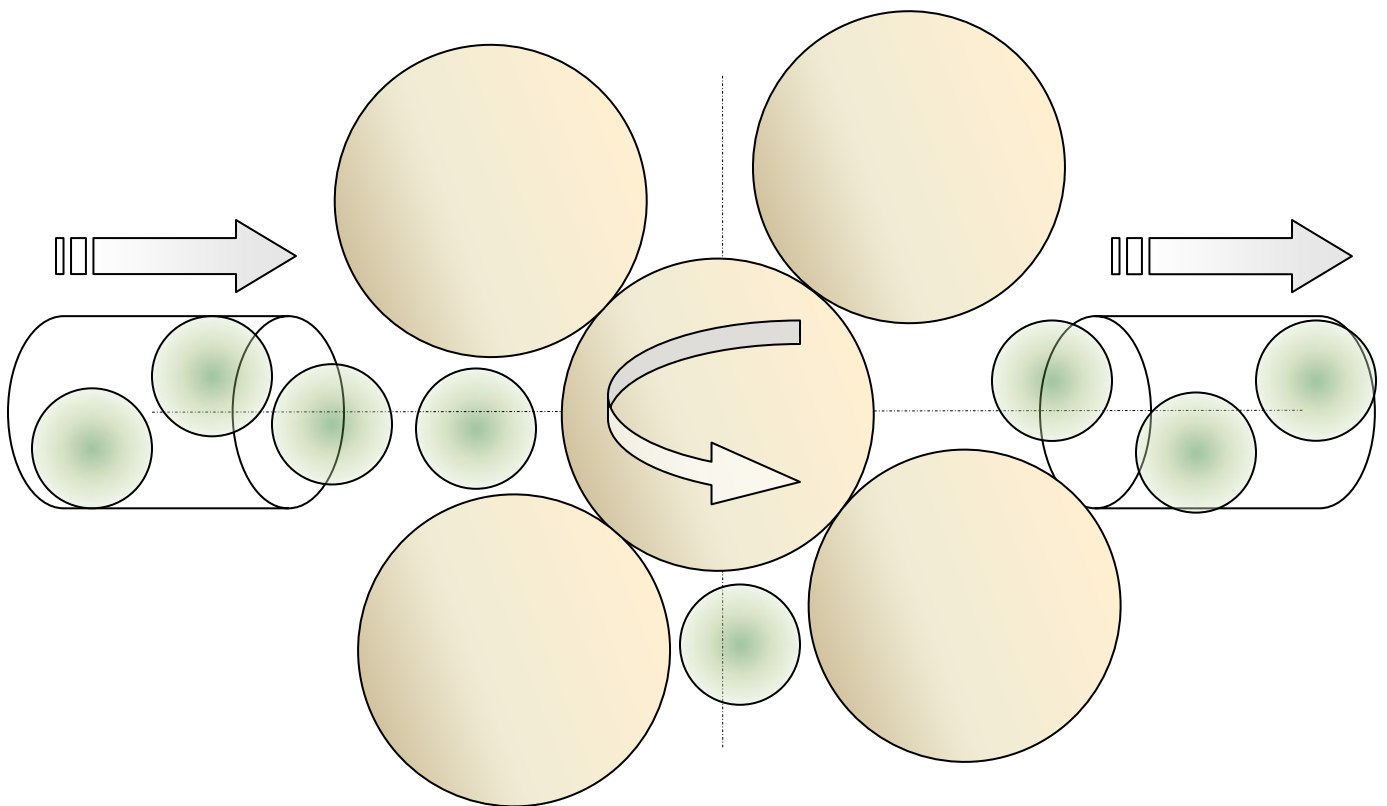


Figure 2 - Angular acc. with two lasers

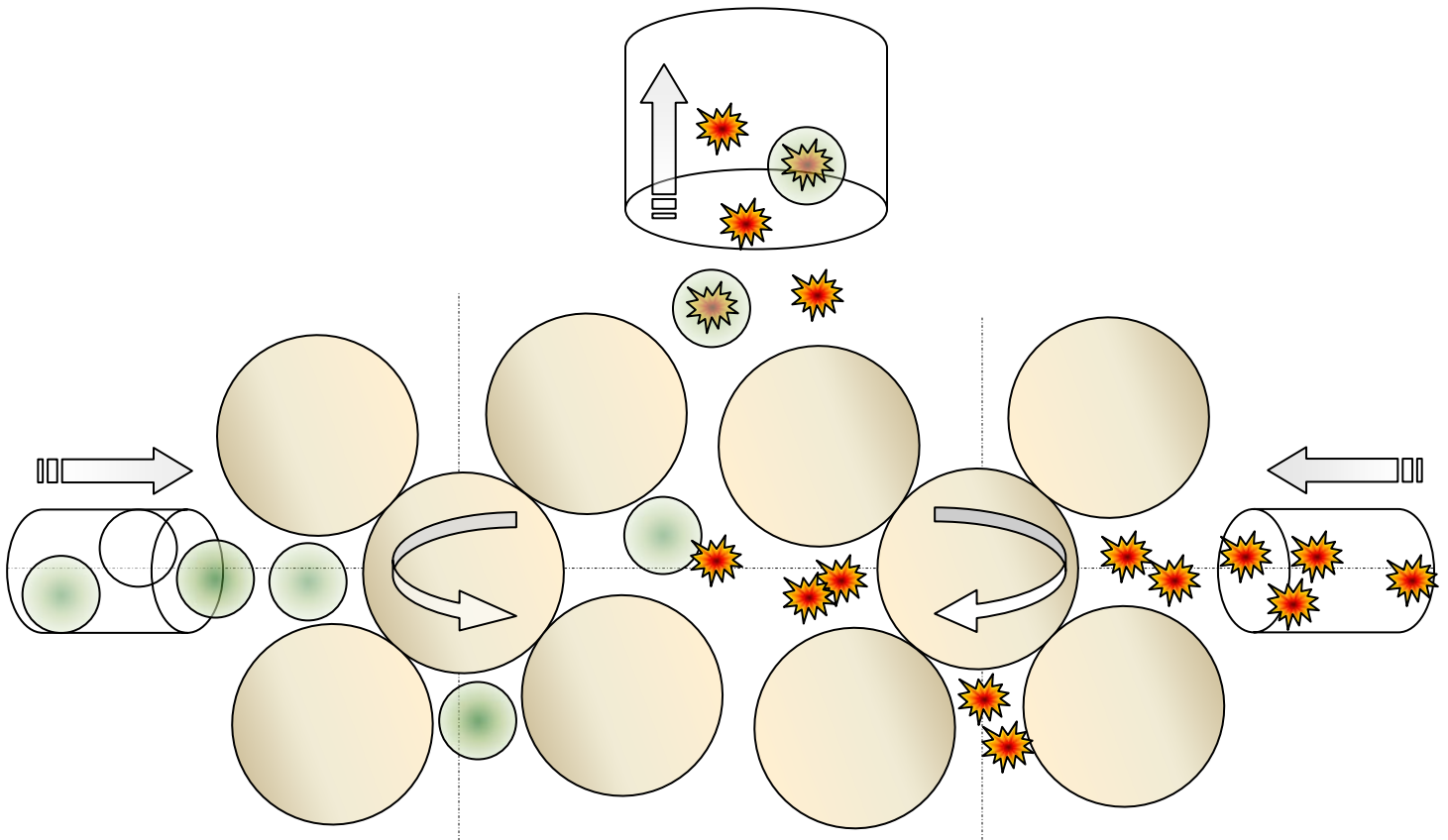
The proposed mechanism has given us the building block of an optical rotor. A brief investigation into proposed and published papers shows that this idea, with the intersecting beams, has some original merit. Proposed experiments that come close are similar in form to (2), where either the structure of the object facilitated the rotation, or the beam itself changed polarization and position to induce a rotation. While the experimental setup of two intersecting optical traps may be difficult, this mechanism only requires two steady state beams with variable amplitude and micron sized beads, all of which available to any optical lasing laboratory.

We now turn our attention to the possible uses of our optical rotor. The first proposed device consists of four rotating beads centered around a central bead. This cross configuration would not be hard to fabricate if each bead had four sites it could bond to at equally spaced polar angles. As the beads rotate they can pick up a target from the left tube which is being lightly forced towards the beads. After half a rotation the beads exit along the right tube that has a small suction force pulling the targets away from the rotor. The entire system is enclosed to prevent the targets from escaping from the rotor until they are supposed to.



If the spacing between the beads is slightly larger than the targets the system will pickup at most one target each quarter rotation. This ‘molecular dispenser’ can serve to precisely control quantizes of biological reactants which would otherwise be hard to control. The advantage of this setup over other single-molecule methods such as traditional optical tweezing and atomic force microscopy, is the indifference to the actual targets. In optical tweezing, the targets must either be dielectric or bind to something that is. AFM requires a host of technical hurdles and also requires the target to bind to a surface. This setup poses no such challenges, though admittedly one cannot perform any measurements of the targets, but only redirect their motion.

The other proposed experiential design builds off the previous one, but is far more elaborate. This system consist of two rotors, operating with anti-parallel spins side-by-side. As the rotors spin they bring their contents together after half a rotation.



As the two different targets mix, they are then rotated another quarter turn to be released into a heterogeneous population. Consider a specific example where the first target represents a small bacterium and the second, a virus that could potentially attack the cell. In this arrangement a specific dosage or at least an average dosage could be given to each cell. If a conformational change happens during infection, the event could be observed and the reaction recorded. In fact, if the process were completely observable, the entire time evolution of the infection could be observed. With one quarter revolution, the entire process could be observed again with an uncontaminated cell! While this does not admit any new physics or biological observations (anything observable here would be possible under conventional method), it allows the process to be extraordinarily

streamlined. To observe the time-evolution in a traditional manner, one would mix the samples, point the microscope and start recording at various intervals of infection. This process allows the observation of the complete cycle with a precise repeatability.

These experimental setups are not without the own technological hurdles. Enclosing the apparatus may be just as challenging as setting up the rotor itself. I do not believe that the bead binding is an issue using conventional optical tweezing, the process would not be difficult, unless a binding mechanism of sufficient strength does not exist. Also, viscous effects were not considered in this paper, and may have a significant impact on the power of the rotors, especially if they get caught in a 'dead-zone' at one of the axes. Despite this, I believe that these are hurdles that can, and should be surmounted due to the high potential gains.

References – Note: All pictures were illustrated by the author

- (1) *Detection of sub-8-nm movements of kinesin by high-resolution optical-trap microscopy*, Chris M. Coppin, Jeffrey T. Finer, James A. Spudich, And Ronald D. Vale, Proc. Natl. Acad. Sci. USA, Vol. 93, pp. 1913–1917, March 1996, Biophysics
- (2) *Mode switching of an optical rotor*, Takahiro Harada and Kenichi Yoshikawa, Applied Physics Letters -- December 16, 2002 -- Volume 81, Issue 25, pp. 4850-4852
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