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Electric Tweezers: Experimental Studies of Positive Dielectrophoresis-Based Positioning and Orientation of a Nanorod

Brian Edwards  
*University of Pennsylvania*

Nader Engheta  
*University of Pennsylvania*, engheta@ee.upenn.edu

Stephane Evoy  
*University of Alberta*

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Electric Tweezers: Experimental Studies of Positive Dielectrophoresis-Based Positioning and Orientation of a Nanorod

Abstract
The manipulation of individual micrometer sized objects has been the focus of significant research efforts over the last few years. A previously proposed method for the arbitrary manipulation of nanoparticles is experimentally demonstrated. This method employs dielectrophoretic forces for the planar control of the motion and orientation of such nanoparticles between a set of microfabricated electrodes. Each electrode is approximated as a set of sources, namely, an unknown point charge and induced dipole. Imposing constraints on the electric field at the location of the particle and requiring self-consistency uniquely determine the sources. They can then be subsequently used to determine the set of electrode voltages that creates an electric field that will produce the prescribed orientation and force on the particle. The drag coefficients of a nanorod are experimentally determined by sequentially applying a constant force both parallel and perpendicular to its axis and observing a resulting motion. With the drag coefficients in hand, the velocity rather than force can be prescribed, and the rod is directed to move accurately at oblique angles to its orientation. The rod is in a constant state of unstable equilibrium and requires negative feedback to maintain a fixed position. The automation of such feedback is demonstrated, allowing a controlled travel of the nanostructures over complex paths.

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Electric tweezers: Experimental study of positive dielectrophoresis-based positioning and orientation of a nanorod

Brian Edwards and Nader Engheta
Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, Pennsylvania 19104

Stephane Evoy
Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta T6G 2E1, Canada and National Institute for Nanotechnology, University of Alberta, Edmonton, Alberta T6G 2E1, Canada

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The manipulation of individual micrometer sized objects has been the focus of significant research efforts over the last few years. A previously proposed method for the arbitrary manipulation of nanoparticles is experimentally demonstrated. This method employs dielectrophoretic forces for the planar control of the motion and orientation of such nanoparticles between a set of microfabricated electrodes. Each electrode is approximated as a set of sources, namely, an unknown point charge and induced dipole. Imposing constraints on the electric field at the location of the particle and requiring self-consistency uniquely determine the sources. They can then be subsequently used to determine the set of electrode voltages that creates an electric field that will produce the prescribed orientation and force on the particle. The drag coefficients of a nanorod are experimentally determined by sequentially applying a constant force both parallel and perpendicular to its axis and observing a resulting motion. With the drag coefficients in hand, the velocity rather than force can be prescribed, and the rod is directed to move accurately at oblique angles to its orientation. The rod is in a constant state of unstable equilibrium and requires negative feedback to maintain a fixed position. The automation of such feedback is demonstrated, allowing a controlled travel of the nanostructures over complex paths. © 2007 American Institute of Physics. [DOI: 10.1063/1.2753584]

I. INTRODUCTION

There have been significant efforts toward developing “touchless” electromagnetic positioning systems for micron- and nanometer sized particles. As opposed to micromanipulators and atomic force microscopy, touchless technologies represent a method to apply gentle forces to small, delicate particles while simultaneously removing the difficulties of stiction. Lab-on-a-chip, heterogeneous integration of electronic components, and studies in nanofluidics all have previously benefited from these tools.

Various tools have emerged to fill this need. The most well known and powerful optical tweezers use a finely focused laser as the electromagnetic source to allow the arbitrary positioning of very small objects, but they are limited by the laser spot size and are costly. Magnetic tweezers have recently been reported, wherein a magnetic particle is controlled using the magnetic field generated by an array of coils. Additionally devices based on electrophoresis and electro-osmotic fluid flows have been demonstrated.

Nevertheless, with the work of Pohl, dielectrophoresis has remained very attractive because of the ease with which electric field gradients can be generated on very small scales with microelectrode structures. Many dielectrophoresis techniques have emerged such as positive dielectrophoresis, negative dielectrophoresis, and traveling wave dielectrophoresis. These techniques have been applied to a variety of materials including carbon nanotubes, DNA, and biological entities such as cancerous cells. However, as opposed to optical tweezers and magnetic tweezers, to date these techniques have only been used to direct particles toward or away from electrodes. This discretizes the space so that the particles can only be controlled with a spatial resolution similar to that of the electrode array itself.

We present and experimentally demonstrate a method to move arbitrarily a particle in the region between an array of five electrodes. This technique combines the low cost of electrokinetic devices with the flexibility of optical and magnetic tweezers.

II. GENERATING AN ELECTRIC FIELD THAT SATISFIES A SET OF LOCALLY DEFINED CONSTRAINTS USING A SET OF ELECTRODES

In this section we will relate the force and orientation of a particle to a set of electrode voltages. A more complete and general derivation has been presented elsewhere.

While it is ultimately the voltage on each of \( n \) electrodes that will be experimentally controlled to direct the force \( F_x \) and \( F_y \) and orientation \( \theta \) of a particle at position \( R \), it is more tractable to consider each electrode as a point charge \( q_i \) and an induced dipole \( \left( p_{x,i} \right) \) and \( \left( p_{y,i} \right) \) at a location \( \vec{r}_i \) (Fig. 1). The voltage field is approximated as the sum of the contributions of the point charges and dipoles from each electrode. For a point \( \vec{R} \) external to the electrodes the voltage field is

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**Electronic mail:** brianedw@seas.upenn.edu

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While for a point \( \vec{r}_i \) internal to the electrode \( i \) the voltage field is

\[
V[\vec{r}_i] = \frac{q_i}{C_i} + \sum_{j=1, j \neq i}^{n} (q_j G_{ij}[\vec{r}_i, \vec{r}_j] + p_{xj} G_{pj}[\vec{r}_i, \vec{r}_j] + p_{yj} G_{pj}[\vec{r}_i, \vec{r}_j]),
\]

(2)

where \( G_{ij}, G_{pj}, G_{pj} \) are Green’s functions for each source.

The dipole on each electrode \( i \) is induced by all other sources, and therefore is dependent on the electric field at \( \vec{r}_i \) through

\[
p_{xi} = -\alpha_{xi} \partial_{x} V[\vec{r}_i],
\]

\[
p_{yi} = -\alpha_{yi} \partial_{y} V[\vec{r}_i].
\]

(3)

where \( \alpha_{xi} \) and \( \alpha_{yi} \) are the polarizabilities of the electrode \( i \) where \( i \) ranges from 1 to \( n \).

The particle can be approximated as an induced dipole \( \vec{p}_{\text{part}} \) with a maximum real polarizability \( \alpha_{\text{part}} \). Note that \( \alpha_{\text{part}} \) could, in fact, be a negative number as is common in many biological particles over certain frequency ranges. An induced dipole will tend to orient along the electric field. Therefore, it is assumed that \( \vec{p}_{\text{part}} = \alpha_{\text{part}} \vec{E}_0 \), where \( \vec{E}_0 \) is an electric field sufficient to hold the particle orientation against all destabilizing factors. Since the orientation \( \theta \) of the particle and \( \vec{E}_0 \) are prespecified, the voltage field is further constrained by

\[
\cos(\theta) \vec{E}_0 = -\partial_{x} V[\vec{R}],
\]

\[
\sin(\theta) \vec{E}_0 = -\partial_{y} V[\vec{R}].
\]

(4)

The force \( (F_x \) and \( F_y \)) on a particle at \( \vec{R} \) can be determined by taking the negative gradient of the particles’ potential energy

\[
U = -\vec{p}_{\text{part}} \cdot \vec{E} = -\alpha_{\text{part}} \vec{E}_0^2. 
\]

This further constrains the voltage field with

\[
F_x = -2 \alpha_{\text{part}} E_0 (\cos(\theta) \partial_{x} V[\vec{R}] + \sin(\theta) \partial_{y} V[\vec{R}]),
\]

\[
F_y = -2 \alpha_{\text{part}} E_0 (\cos(\theta) \partial_{y} V[\vec{R}] + \sin(\theta) \partial_{y} V[\vec{R}]).
\]

(5)

With each electrode there are three unknown sources \( (q_i, p_{xi}, \) and \( p_{yi}) \) and two constraints in Eq. (3), leaving one degree of freedom per electrode. However, Eqs. (4) and (5) form an additional four constraints. Therefore, it would initially appear as if four electrodes would be sufficient to provide as many degrees of freedom as constraints. However, there exist many pathological combinations of particle position, angle, and applied force, for which no solution set of voltages exists.28

Adding an extra electrode resolves this problem. However, to maintain a linear relationship an extra arbitrary constraint is added

\[
0 = \sum_{i=1}^{n} q_i. 
\]

(6)

With a particle position, orientation, and desired force, the constraints imposed in Eqs. (3)–(6) can be solved for the unknown electrode point charges and dipoles using linear techniques such as matrix inversion. This solution set can be applied back into Eq. (2) to find the voltage required on each electrode.

In Fig. 2, the concept is illustrated. The lines of constant voltage are plotted in the plane of the electrodes and the potential energy of the particle is projected on a vertical axis below. The electrode voltage set is calculated that orients a single particle at the center of the array to an angle of 45° with no applied force. It is evident that the particle is oriented in the desired direction by noting the lines of constant
The electric field was generated by a circular array of five gold electrodes, each 40 μm in diameter, spaced on a circle of 200 μm diameter, fabricated using standard lithographic and etching techniques. A drop of particle suspension could be placed onto the electrode set and sealed using a silicone spacer and a coverslip.

The voltage for each of the five electrodes was generated by five 8 bit digitally controlled potentiometers, each providing two lines at potentials of +Vi and −Vi. Note that +Vi could be positive or negative. Five high speed multiplexers switched between these two voltages at frequency fc = 500 kHz, to produce the five square-wave signals. The digital potentiometers were attached to a universal serial bus (USB)-digital output board which was controlled through a LABVIEW application.

The LABVIEW application calculated the proper electrode voltages using input from the user and real-time video of the particle and electrodes. The program can automatically track position of the particle, R, through image analysis. The application’s main loop cycled at 7.5 Hz.

The force applied was always less than or equal to 76 N, and the electric field applied to the particle was maintained at 10 kV/m. The voltage on each electrode never exceeded a magnitude of 10 V.

V. CAPTURING A ROD, CONTROLLING THE FORCE, AND DETERMINING THE DRAG COEFFICIENTS

A dilute suspension of rods was placed over the electrode array and the rods quickly settled to the glass substrate. Within the region bounded by the electrode array there were seven rods. A cursor, indicating R, was placed over one of the rods near the center of the array. When the electrodes were activated, the indicated rod quickly aligned with the electric field. Being in regions of strong potential field gradient, all other rods quickly moved to nearby electrodes. However, the indicated rod remained balanced. As the rod drifted due to Brownian motion and small errors in modeling, the program tracked the rod’s position through image analysis attempting to maintain zero force on it. At this point an arbitrary force can then be applied to a particle.

The rod was oriented at 90° so that forces applied in the y direction are parallel to the rod orientation and forces along the x direction are perpendicular to the rod orientation.
Forces in the $x$ and $y$ directions were applied to move the rod around the array while observing the resulting motion. Averaging the ratio of the velocity to the force in the $y$ direction yielded an experimental parallel drag coefficient of $21 \times 10^{-9}$ N s/m which is reasonably close to the theoretical value. Additionally, averaging the ratio of the velocity to the force in the $x$ direction yielded an experimental perpendicular drag coefficient of $15 \times 10^{-9}$ N s/m which is also reasonably close to the theoretical value.

**VI. CONTROLLING THE VELOCITY**

Since the rod has different drag coefficients perpendicular and parallel to its axis, applying an oblique force will not yield a velocity in the same direction. To determine the proper force to yield a specific velocity, we first project the desired velocity into a parallel and perpendicular component, find the required force parallel and perpendicular to the rod axis, and then project these forces back onto the normal $x$-$y$ axes.

$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = M_{\theta} \begin{pmatrix} C_x \\ 0 \\ 0 \\ C_y \end{pmatrix} \cdot M_{\theta}^{\dagger} \begin{pmatrix} V_x \\ 0 \\ 0 \\ V_y \end{pmatrix},$$

(7)

where $M_{\theta} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}$.

The rod was directed to move at an angle of $45^\circ$ to its orientation. In Fig. 5 it can be seen that the force (green) and velocity (aqua) are not in the same direction, but if the force is chosen according to Eq. (7), the velocity may be specified in controlling a nanorod. This is evident as the rod appears several seconds later along the path of specified velocity not the vector of the force.

**VII. CONTROLLING THE POSITION**

Approximate velocity can be defined as the difference between the two positions divided by time. Given a target position $\vec{R}_T$, the velocity needed to return a rod to this point is $\{V_x, V_y\} = (\vec{R}_T - \vec{R}) / T$, where $T$ is the time between the cycles of the program.

By using image analysis, the position of the rod can constantly be compared to the target position and using Eq. (7), a force can be calculated that will return the rod to that location. It is evident in Fig. 3 that this represents a stabilizing negative feedback loop. It is also evident in Fig. 2 that this is necessary because even when no force is being applied, the rod is only metastable. Brownian motion and modeling noise are sufficient to disturb the rod out of this equilibrium position; however, the negative feedback loop allows a rod to be balanced indefinitely.
The target position can be a function of time, $\tilde{t}(t)$, with an associated angle, $\theta(t)$, to allow complex paths to be pre-programmed (Fig. 6).

VIII. SUMMARY

A method has been presented to move and orient accurately a prolate conductive particle by properly calculating the voltage on a surrounding array of electrodes. This method has been demonstrated on a gold nanorod to determine its drag coefficients, direct motion along an oblique angle, and direct the rod over a complex path. Possible applications of this technology include lab-on-a-chip, heterogeneous integration of electronic components, and microfluidic studies.

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30See EPAPS Document No. E-JAPIAU-102-017714 for animated simulations and experimental video. This document can be reached via a direct link in the online article’s HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html).