Electric tweezers: negative dielectrophoretic multiple particle positioning

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**Abstract.** Electric tweezers are a touchless positioning apparatus that employs dielectrophoresis and electroorientation to arbitrarily position cell-sized particles. In this paper, we develop an algorithm which enables electric tweezers to operate on multiple particles. Furthermore, we probe the limits of this technique in simulation, examining the range of electric field magnitudes and forces that can be applied. We then demonstrate this new functionality on two particles. The device can apply forces on any particle of non-zero polarizability and here this is highlighted by manipulating negatively polarized glass beads. Additionally, we demonstrate that negligibly polarized particles can also be manipulated through mechanical forces applied by other particles.

Online supplementary data available from stacks.iop.org/NJP/14/063012/mmedia

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Historically, our ability to observe has preceded our ability to control. Microscopes that can resolve living cells have existed for hundreds of years [1], but we have only begun to be able to manipulate these cells individually. Recently, within different engineering and scientific disciplines, we have seen a plethora of new techniques for controlling objects. Here, we will focus on manipulation techniques aimed at cell-sized objects [2–5], and specifically acknowledge the unique niche that atomic force microscope [6, 7] and scanning tunneling microscope [8] techniques hold in their ability to position individual atoms.

Several of these techniques follow a more conventional tweezer design [9–11]. However, for small objects, surface forces (i.e. stiction) may dominate body forces (i.e. gravity), making disengagement from an object difficult [12, 13]. Therefore, many efforts focus on the development of touchless-based technologies. Much of this work exists in the lab-on-a-chip community to create a variety of powerful methods to interrogate, sort and manipulate cells in parallel and en masse [14–21]. Conversely, several technologies can position single particles at discrete locations, but cannot arbitrarily and reversibly manipulate them [22–26]. Some others can move objects from one discrete location to another [27, 28].

Of the touchless techniques that can arbitrarily and individually position particles, optical tweezers [29–31] and optoelectronic tweezers [32–34] operate by dynamically positioning potential energy minimums. In contrast, magnetic tweezers [35–37], electroosmotic fluid drag manipulation [38, 39], electrophoretic manipulation [40–42] and dielectrophoretic manipulation [43] operate by applying potential energy gradients, and they often require negative feedback to maintain the position of the particles. By the very nature of the aforementioned techniques, arbitrary movement of multiple particles, controlled by relatively few degrees of freedom, is a technological challenge [38, 39].

Electric tweezers [43–45] operate by tailoring the electric field at the location of each particle in order to provide an orienting torque [46–49] and lateral forces via dielectrophoresis [50, 51]. In this paper, we develop and demonstrate multiple particle functionality in electric tweezers. This is enabled through a new, numerically efficient algorithm. By way of numerical simulation, we explore the limits of the orienting electric field magnitude and force magnitude that can be achieved for single particles. Additionally, we look at how these are affected by multiparticle configurations. Experimentally, we demonstrate simultaneous control of two particles.

Biological cells, an important class of particle, can be negatively, positively or negligibly polarized, depending on the electric field frequency [52, 53]. Electric tweezers are unique among dielectrophoretic devices in their ability to apply controlled forces to particles that are positively or negatively polarized, even in the same experiment. In previous work, we manipulated a positively polarized particle. Here, we demonstrate the manipulation of negatively polarized particles. Additionally, we demonstrate that negligibly polarized particles can be mechanically driven via applied forces from polarized particles. In this latter ‘bull dozing’ technique, many particles can be manipulated serially.

Electric tweezers apply feedback-regulated forces, and therefore can create a virtual particle trap at any location in space. Consequently, electric tweezers represent a dielectrophoretic analog to the electrophoretic anti-Brownian electrokinetic (ABEL) trap, wherein the trap stiffness is determined by the available force magnitude and the feedback time constant.

Not insignificantly, we also demonstrate that electric tweezers can be rendered onto a single inexpensive printed circuit board (PCB) placed on an entry-level microscope. The electric tweezers project represents an attempt to create an affordable alternative to optical tweezers.
Figure 1. Schematic showing $N = 2$ particles surrounded by $n = 10$ electrodes, in which both particles have negative polarizabilities. The desired force and orientations are shown by the green and orange arrows, respectively. These inputs were used to calculate voltages on each electrode and those voltages were then used to generate the lines of constant voltage shown in the plane of the particles and the dipole potential $-|\mathbf{E} \cdot \mathbf{E}|$ projected on the false axis below. From the calculated fields, we see that there is indeed an electric field in the $+\mathbf{x}$-direction at the location of each particle, and that $-\alpha_i \mathbf{E} \cdot \mathbf{E}$ decreases in the $+\mathbf{y}$-direction and $-\mathbf{\hat{x}}$-direction for particles 1 and 2, respectively. This indicates that the desired force and orientation have been achieved.

1. Theory

The goal of the following derivation is to determine a numerical method to quickly calculate the voltages of a set of electrodes (labeled $j$ from 1 to $n$) that will cause a set particles (labeled $i$ from 1 to $N$) to move and orient simultaneously, as shown in figure 1. To achieve this task, we will control the electric potential ($V[\mathbf{r}]$) and several derivatives thereof at the location of each particle ($\mathbf{R}_i$). Both the particles and the electrodes are represented by a multipole expansion truncated at the second term. Generally, this will be accurate enough, provided that the particles are separated by greater than a particle diameter from other particles and by greater than an electrode diameter from the electrodes. Furthermore, we will consider the electrodes’ effect on particles and electrodes, but ignore the particles’ effect on electrodes and each other.

The $i$th particle will tend to orient to minimize its potential energy

$$U_i = -\mathbf{p}_i \cdot \mathbf{E}[\mathbf{R}_i] = - (\alpha_i \cdot \mathbf{E}[\mathbf{R}_i]) \cdot \mathbf{E}[\mathbf{R}_i],$$

(1)

where $\mathbf{p}_i$ is the dipole moment of the particle, and $\alpha_i$ is the polarizability matrix [54] of the particle. The induced dipole moment is dependent on the orientation of the particle, but for some orientation it will be maximized so that $\mathbf{p}_i = \alpha_{i,\text{max}} \cdot \mathbf{E}[\mathbf{R}_i]$ where $\alpha_{i,\text{max}}$ is the maximum principle polarizability component. For certain particle shapes, solution permittivities, and particle permittivities, the maximum principle polarizability component may in fact still be negative [51]. Therefore, the orientation of the $i$th particle can be controlled by specifying the
yields a transformation matrix
\[ \frac{\partial}{\partial x} V[R_i], \]
where $E_i$ and $\theta_i$ is an electric field magnitude and angle of our choosing such that it is strong enough to hold that orientation against randomizing effects such as Brownian motion. It is of note in equation (1) that if $E[R_i]$ is an angular potential energy minimum, then $-E[R_i]$ is also. In this way, the electric field can be reversed with no effect on particle orientation.

Unfortunately, it is impossible to create a local potential minimum with respect to space for positively polarized particles using static fields in a source free region [45]. Rather, by employing active negative feedback the position of a particle can be controlled regardless of the sign of its polarizability. Again the potential energy of the $i$th particle is $U_i = -\mathbf{p}_i \cdot \mathbf{E}[R_i]$. If we now assume that the particle has oriented such that the direction of maximum polarizability is oriented along the electric field, then the potential energy becomes
\[ U_i = -\alpha_{\text{max},i} \mathbf{E}[R_i] \cdot \mathbf{E}[R_i]. \]
The force on the $i$th particle is $F_i = -\nabla U_i$ or rather
\[
\begin{align*}
F_{x,i} &= -2E\alpha_{\text{max},i} \left( \cos[\theta_i] \partial_{x,x} V[R_i] + \sin[\theta_i] \partial_{x,y} V[R_i] \right), \\
F_{y,i} &= -2E\alpha_{\text{max},i} \left( \cos[\theta_i] \partial_{x,y} V[R_i] + \sin[\theta_i] \partial_{y,y} V[R_i] \right).
\end{align*}
\]
Note that force may be specified on both particles with $\alpha_{\text{max},i} > 0$ and $\alpha_{\text{max},i} < 0$ yielding control via positive and negative dielectrophoresis, respectively. Again, it is of note in equation (1) that the gradient of $U_i$ is equivalent for an electric field $\mathbf{E}[R]$ and $-\mathbf{E}[R]$.

Examining equations (2) and (3), it is evident that we must be able to control $\partial_x V[R_i]$, $\partial_y V[R_i]$, $\partial_{x,x} V[R_i]$, $\partial_{x,y} V[R_i]$ and $\partial_{y,y} V[R_i]$ for each particle $i$ from 1 to $N$. A relatively easy way to do this is to surround the particle with an array of $n$ electrodes, each at a position $\mathbf{r}_j$ and approximated as a point charge $q_j$ and dipole with components $p_{xj}$ and $p_{yj}$. The electric potential $V[R]$ reasonably far away from the electrodes may be approximated as
\[ V[R] \equiv \sum_{j=1}^{n} \left( q_j G_q[R, \mathbf{r}_j] + p_{xj} G_{p_x}[\mathbf{R}, \mathbf{r}_j] + p_{yj} G_{p_y}[\mathbf{R}, \mathbf{r}_j] \right), \]
where $q_j$, $p_{xj}$ and $p_{yj}$ are the point charges and dipoles used to approximate the field generated by each electrode and $G_q$, $G_{p_x}$ and $G_{p_y}$ are the Green functions of those sources.

The voltage on electrode $j$ is related to the sources through $V_j = V[\mathbf{r}_j]$ where the singular points are defined as $G_q[\mathbf{r}_j, \mathbf{r}_j] \equiv 1/C_{\text{elec}}$, $G_{p_x}[\mathbf{r}_j, \mathbf{r}_j] \equiv 0$ and $G_{p_y}[\mathbf{r}_j, \mathbf{r}_j] \equiv 0$. Similarly, the induced dipoles on electrode $j$ are proportional to the electric field at $\mathbf{r}_j$ and therefore $\partial_x V[\mathbf{r}_j] \equiv 0$ and $\partial_y V[\mathbf{r}_j] \equiv 0$ where the singular points are defined as $\partial_x G_{p_x}[\mathbf{r}_j, \mathbf{r}_j] \equiv -1/C_{\text{elec}}$, $\partial_y G_{p_y}[\mathbf{r}_j, \mathbf{r}_j] \equiv 0$ and $\partial_x G_{p_x}[\mathbf{r}_j, \mathbf{r}_j] \equiv 0$.

Evaluating $V_j = V[\mathbf{r}_j]$, $\partial_x V[\mathbf{r}_j] \equiv 0$ and $\partial_y V[\mathbf{r}_j] \equiv 0$ for each electrode $j$ from 1 to $n$ yields a $3n \times 3n$ system of linear equations. This can be rendered into a numerical transformation matrix $\mathbf{T}$ which converts between the voltages $V_j$ and the sources $q_j$, $p_{xj}$ and $p_{yj}$ so that $\mathbf{S} = \mathbf{T} \cdot \mathbf{V}$. Note that since we ignore particle effect on electrodes, $\mathbf{T}$ is only a function of the electrode geometry and it only needs to be calculated once.

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Using this transformation matrix we can express the constraints in equations (2) and (3) using (4) as

\[
\begin{align*}
E_i \cos[\theta_i] &= A_{E_x,i} \cdot \mathbf{T} \cdot \mathbf{V}, \\
E_i \sin[\theta_i] &= A_{E_y,i} \cdot \mathbf{T} \cdot \mathbf{V}, \\
F_{x,i} &= A_{F_{x,i}} \cdot \mathbf{T} \cdot \mathbf{V}, \\
F_{y,i} &= A_{F_{y,i}} \cdot \mathbf{T} \cdot \mathbf{V}.
\end{align*}
\] (5)

These constraints may be expressed for each particle \(i\) and then collected to form a system \( \mathbf{B} = \mathbf{K} \cdot \mathbf{V} \), where \( \mathbf{B} \) and \( \mathbf{K} \) are known quantities containing the particle positions, desired force and orientation of each particle. Our goal then becomes to find the set of electrode voltages (\( \mathbf{V} \)) which satisfies this system.

If we have four electrodes per particle this system is generally determined, but in some pathological situations it is unsolvable and near these pathological conditions the voltages necessary are so large as to be unrealistic [44]. Additionally, it may not be convenient to require exactly four electrodes per particle.

Therefore, we assume that we have at least five electrodes per particle and that in addition to the system above, we also desire to minimize the voltages to ease the burden on the equipment. In other words, we formulate the problem as \( \min(\mathbf{V} \cdot \mathbf{V}) \) such that \( \mathbf{B} = \mathbf{K} \cdot \mathbf{V} \). This can be conveniently formulated into matrix operations and solved using the method of Lagrange multipliers as

\[
\begin{pmatrix}
\mathbf{V}_n \\
\lambda_{4N}
\end{pmatrix} = \begin{pmatrix}
\mathbf{I}_{n \times n} & (\mathbf{K}^T)_{n \times 4N} \\
\mathbf{K}_{4N \times n} & \mathbf{0}_{4N \times 4N}
\end{pmatrix}^{-1} \cdot 
\begin{pmatrix}
\mathbf{0}_n \\
\mathbf{B}_{4N}
\end{pmatrix},
\] (6)

where \( \mathbf{I} \) is the identity matrix, \( \mathbf{0} \) is the zero matrix and \( \lambda \) is a list of Lagrange multipliers where subscripts denote size. This formula can be used to determine electrode voltages that will orient and apply prescribed forces on a set of particles of known position.

As we have stated earlier, a particle will feel equivalent torque and force in an electric field \( \mathbf{E}[\mathbf{R}_i] \) and \( -\mathbf{E}[\mathbf{R}_i] \) and, therefore, if \( \mathbf{V} \) is a solution to \( \mathbf{B} = \mathbf{K} \cdot \mathbf{V} \), then \( -\mathbf{V} \) will produce identical effects. While the particles are approximated using the first two terms of a multipole expansion, we may ignore the first term \( (q_i) \) and the resulting electrophoretic forces, by creating a system which rapidly alternates between \( \mathbf{V} \) and \( -\mathbf{V} \).

It is worth noting that this technique can be used with different linear constraints to yield different functionality. For instance, a multiparticle version of the electrophoretic ABEL trap could easily be rendered if we do not alternate the voltages and replace equations (2) and (3) with

\[
F_{x,i} = -q_i \partial_x V[\mathbf{R}_i] \quad \text{and} \quad F_{y,i} = -q_i \partial_y V[\mathbf{R}_i].
\]

2. Simulation

Electric tweezers will cease to be effective when the calculated voltages exceed that available from the experimental setup. There are numerous variables in the system, including particle size and material, electrode size and arrangement, and the properties of the surrounding medium. These are all combined through numerically inverted matrices, making simple analytical rules-of-thumb difficult to calculate. However, by exploring several prototypical situations, we can gain some insights into the limits of the electric tweezers.
In the following simulations, we highlight a system in which the electrode array consists of ten electrodes, each 40 \( \mu \text{m} \) in diameter, equally spaced on a circle 150 (\( \mu \text{m} \)) in diameter. The particles are \( d = 4.7 \mu \text{m} \) glass beads with a permittivity of \( \varepsilon = 4\varepsilon_0 \). The surrounding medium is water with a permittivity of \( \varepsilon_m = 81 \varepsilon_0 \) and a dynamic viscosity of \( \mu = 1 \times 10^{-3} \text{ Pa s} \). This yields a particle polarizability of \( \alpha = -5.35 \times 10^{-26} \text{ (F m}^2) \) and a drag coefficient of \( C_D = 3\pi \mu d = 4.42 \times 10^{-8} \text{ N s m}^{-1} \). This polarizability corresponds to a Clausius–Mossotti factor of nearly \(-1/2\). We will consider a prototypical velocity to be \( v_0 = 4.7 \mu \text{m s}^{-1} \) and force to be \( f_0 = v_0 C_{\text{Drag}} = 0.21 \text{ pN} \). The hardware has a range of \(-10\) to \(+10\) volts.

The electric field magnitude at the location of a spherical particle is arbitrary because particle orientation is irrelevant. However, large electric field magnitudes will intuitively require large electrode voltages. Additionally, in the event of an applied force, small electric field magnitudes will also require large electrode voltages in which the difficulty lies in creating a potential energy gradient for a particle that is near a potential energy minimum. To find a suitable electric field magnitude, let us assume that we have a single glass bead at the center of the electrode array with a force of magnitude \( f_0 \) applied orthogonally to the electric field. Simulating this scenario for varying electric field magnitudes in figure 2(a), we observe that values between 5 and 20 kV m\(^{-1}\) yield the lowest electrode voltages. Electric field magnitudes less than 1 kV m\(^{-1}\) and greater than 50 kV m\(^{-1}\) are impossible.

The force magnitude is also arbitrary. It is intuitive that exceptionally large forces will exceed the hardware bounds. If we assume now that the particle has a fixed electric field of \( E_0 = 10 \) (kV m\(^{-1}\)) we observe in figure 2(b) that forces up to 1.1 pN can be applied corresponding to particle velocities of up to 25 \( \mu \text{m s}^{-1} \). If the voltages are updated at a rate of 30 Hz, it is approximately 50% likely that the particle will have diffused no further than 50 nm. However, within this time step, electric tweezers can correct for diffusion lengths up to 830 nm. Therefore, the electric tweezers’ ability to trap a single particle is theoretically limited by the uncertainty of the relatively coarse refresh rate of the camera.

It is important to note that two particles cannot be brought arbitrarily close to each other. This is due to the fact that one cannot specify the local derivatives of the voltage field to be two different sets of values at the same location. Mathematically, that would create a system \( \mathbf{B} = \mathbf{K} \cdot \mathbf{V} \) which has no solution. A similar issue will arise with any technique in which it is difficult to obtain a highly divergent field. This arises in magnetics for magnetic tweezers, fluid flow for electrophoretic manipulation and electric field in electrophoretic manipulation. However, providing that some distance is maintained, two particles may be independently controlled. Figure 2(c) depicts the voltages required for two particles to pass each other, each with a speed of one particle diameter per second at different particle separations. Each has an electric field magnitude of \( E_0 \) applied in the same direction. Not accounted for in this system is a repulsive interparticle force that is \( f_0 \) at 17 \( \mu \text{m} \), which increases rapidly for smaller separations.

Lastly, it is interesting to note how particle orientation affects the electrode voltages in multiparticle systems. Suppose there are two glass beads separated by a distance of 60 \( \mu \text{m} \), both with a field magnitude of \( E_0 \). In figure 2(d), we observe the voltages required to vary the electric field direction of one of the particles. The voltages required are substantially less when the particles have similar electric field directions.

With elaborated description, figure 1 is reintroduced. There are two glass beads with electric field magnitudes of \( E_0 \) oriented along the \( x \)-axis. One particle has a force \( f_0 \) applied in the \(+y\)-direction, while the other particle experiences a force of \( f_0 \) in the \(-x\)-direction. Upon employing equation (6), a set of voltages is calculated, with the maximum magnitude of 2.7 V.
Figure 2. Electric tweezer limitations. The device will cease to work when the calculated voltages exceed the hardware range, which is from $-10$ to $+10$ volts. Here we choose an electrode array design, particle type and fluid medium and use these to explore the (a) electric field limitations, (b) force limitations, (c) particle separation limitations and (d) particle configuration limitations. The green arrows show the applied force while the orange arrows show the electric field directions at the location of each particle.

Those voltages are used to find the electric potential field and dipole potential distribution. Indeed, we see these voltages yield the expected results as $E$ is pointing in the desired direction at both particle locations and that the slope of $-|E \cdot E|$ at each particle is such that the particle will experience a force in the desired direction. It is important to realize that first the force and orientation are chosen and then a physically viable field which satisfies these constraints is found after. It is also apparent that the fields only satisfy the constraints within a limited region around each particle. For the configuration in figure 1, this region extends for several microns in all directions before the relative errors in the force reach 20%.

3. Experimental Setup

The experimental setup consists of a dispersion of glass beads ($4.7 \mu m$, $\varepsilon \approx 4\varepsilon_0$, Bangs Laboratories, Inc., SS05N) in deionized water surrounded by a set of 10 electrodes as described previously. The electrodes are evaporated gold, 200 nm thick, and are fabricated on the microscope slide using standard optical lithography techniques. Observing the particles from above is a microscope and video camera as seen in figure 3. The camera images are transferred
Figure 3. Experimental setup. (a) The signal generator is shown in its enclosure with a patterned microscope slide. The design of the PCB and enclosure allow optical access from above and below. It is placed on a microscope stage as seen in (b) and (c). The particles are dispersed in solution in the slide’s centre where the traces converge.

in real time to custom software which tracks particle locations, manages user input, renders a display, and calculates the required voltages $V$ using equation (6).

These voltage values $V$ are sent to a custom PCB and rendered as the amplitudes of ten synchronous bipolar square wave signals wherein the voltage on each electrode is continuously switched between $V$ and $-V$ with a selectable frequency between 1 kHz and 10 MHz. We found high-frequency signals necessary in order to both remove electrophoretic effects and reduce the effects of charge shielding of the electrodes. The necessary frequency is related to the conductivity of the fluid, which for aqueous solutions might be quite high. In order to increase the frequency, the PCB is designed to minimize trace lengths, and therefore capacitances, by surrounding the microscope slide. The limiting factor is the high speed analogue multiplexors used to physically switch between each voltage $V$ and $-V$. The available frequency range was from 1 kHz to approximately 3 MHz. The board is aligned with the slide via a custom enclosure and electrical contact is made with pogo-pins.

The voltages on the electrodes generate an electric field at the location of each particle. The particles will undergo some displacement, partly due to the fields and partly due to Brownian motion. The computer observes their new positions, collects new user input and calculates new voltages. The process repeats at about 30 Hz, synchronized with the refresh rate of the camera. Images were captured only at intervals of several seconds in order to minimize system lag.

It is convenient to run the device in a position control mode in which the user specifies a desired location for each particle, not a desired force. Based on the location of the particle relative to the desired position, the particle’s drag coefficients and a feedback constant, the
computer automatically calculates a virtual restoring force for each particle. The strength of the feedback can be adjusted to act as either a very stiff or a soft virtual spring tethering the particle to a specific location.

While the drag coefficients can be calculated similarly to the polarizabilities, it is often helpful to find them experimentally to make the feedback as accurate as possible. The program also keeps a history of applied forces, orientations and velocities, and uses these to determine average drag coefficients for each of the particle’s principle directions [55–57].

4. Results

In figure 4 (see supplementary Movie 1, available from stacks.iop.org/NJP/14/063012/mmedia) two particles, indicated by the red and blue paths, are moved in a counter-clockwise direction around the center of the electrode array. Both had an applied electric field of 5 kV m$^{-1}$. Both particles were in position-control mode, in which the force on each particle was $F_i = C_D (\mathbf{R}_{\text{target},i} - \mathbf{R}_i) / (\mathbf{s})$ so that 62% of the effects of a perturbation are removed after 1 s. This relatively low feedback provided low-magnitude voltage solutions while providing acceptable responsiveness. The desired location is indicated by the smaller circle, while the larger circle indicates the location $\mathbf{R}_i$ calculated via real-time image processing. The voltages were alternated at a frequency of 1 MHz.

During this demonstration, the calculated voltages stayed within the ±10 V available from the PCB. The user-interface allowed us to move the target location of one particle at a time and, therefore, the particles were moved alternately. However, simultaneous preprogrammed paths...
Figure 5. Still frames from video showing a cluster of three glass beads being used to push a single low polarizability particle. The low polarizability particle is labeled with an arrow. (See supplementary Movie 2, available from (stacks.iop.org/NJP/14/063012/mmedia).

could be easily implemented. When at rest, the particles are always within one micron of their equilibrium position (i.e. precision) and within several microns of their desired positions (i.e. accuracy). The precision could be improved by using more viscous solvents to reduce Brownian motion, stiffer virtual springs and higher frame-rate cameras. The accuracy could be improved by including particle–particle interactions and higher order multipole approximations.

In figure 4, we have manipulated two negatively polarized glass beads, while in previous work \cite{43} we manipulated a single positively polarized gold nanorod. This illustrates a substantial difference between electric tweezers and many other dielectrophoresis techniques. Both negative dielectrophoretic octopole cages \cite{25} and positive dielectrophoretic self-assembly electrodes \cite{22} create static traps using potential energy minima and can be used with only negatively and positively polarized particles, respectively. In this work, the particles are not at a potential energy minimum, but rather are constantly ‘herded’ by a dielectrophoretic force. This technique can be applied to positively and negatively polarized particle simultaneously in the same experiment.

In figure 5, we demonstrate how non-polarized particles can be mechanically driven via applied forces from polarized particles.

Dielectrophoresis has no effect on particles with negligible polarizability. Suppose that the particles of interest have a relatively small polarizability $|\alpha_{max}|$, either because they are similar to the suspension medium, or because the frequency of the square wave signals is intentionally tuned to minimize their polarizability as could be done with biological cells. In either case, these particles will not react to the electric fields around them, but they can be pushed by other particles that have a larger polarizability magnitude.
In figure 5, there is a piece of debris on the microscope slide which undergoes only very weak negative dielectrophoresis. This particle is minimally affected by the electric field. In contrast, a cluster of three glass beads are joined together due to dipole–dipole interactions and are manipulated as a single object undergoing strong negative dielectrophoresis. This particle aggregate is used to push the debris from one side of the microscope slide to the other. This could be used to manipulate many negligibly polarized particles serially, effectively overcoming the $N < 5n$ limitation and allowing one to bring two particles arbitrarily close to each other. Of course, in this case diffusion cannot be countered on unattended particles, and non-electric means would be needed to maintain particle positions, such as shallow recesses in the substrate.

As an aside which bears mentioning, in figure 4 there are four particles not being actively controlled. The nature of a circular array is such that an electric field minimum tends to exist near the center. This can be seen in figure 1 as the central maximum in $-|\mathbf{E} \cdot \mathbf{E}|$ between both particles. Any uncontrolled negatively polarized particles within the array will naturally drift toward this region. Negatively polarized particles outside the array will be pushed far away. In contrast, as seen in our previous work [43], uncontrolled positively polarized particles tended to collect at electrode edges due to positive dielectrophoresis.

5. Conclusion

In this paper, we have extended the theory behind electric tweezers to deal with multiple particles. This has been applied to a two-particle system wherein two glass beads were independently controlled. In contrast to our previous work, these particles were controlled using negative dielectrophoresis, demonstrating the electric tweezer’s ability to control both positively and negatively polarized objects. We have also demonstrated how particles with negligible polarizability, while not affected by the electric fields themselves, can be indirectly controlled.

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