Optical Trapping Techniques for the Control and Actuation of Microstructures

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Optical Trapping Techniques for the Control and Actuation of Microstructures

Alexandre Wetzel, Einstom Engay, Ada-Ioana Bunea, Jesper Glückstad

DTU Nanolab
DTU Fotonik
What will be the topic of this presentation?

1. Optical trapping at the microscale
   i. What is optical trapping at the microscale?
   ii. What are the techniques employed?
   iii. What are the applications?

2. Optical trapping in biological media
   i. Challenges for optical trapping in turbid media
   ii. Wavefront correction algorithms
   iii. Real-time implementation for optical trapping

3. Future perspectives & Conclusions
1. i. What is optical trapping at the microscale?

Objects that can be trapped:
- Atoms
- Fullerenes
- Nanowires and nanotubes
- Graphene
- Molecules
- NV centres
- Quantum dots
- Plasmonic nanoparticles
- Synthetic colloids
- Layered materials
- Cells

Trapping Wavelength

1. i. What is optical trapping at the microscale?

- Trapping force between ~0.1 pN to about ~1.5 nN
- Force is tunable with laser intensity (trap stiffness)
- Precise Position tracking: resolution ~ 2 - 8 nm usually (maximum achieved ~3.4 Å)
- Precise Force tracking: resolution ~0.1 pN


1. ii. What are the techniques employed?

Simple trapping set up (from inverted microscope):

- Microscope objective with a large NA (usually NA > 1).
- The trapping laser is incorporated into the microscope path
- Precision translation stage (piezoelectric actuators)
- Position measurement device (QPD/Camera)
- Optional Integration of characterization techniques (fluorescence, spectroscopy, …)

1. ii. What are the techniques employed?

Steerable traps (1):

- **Scanning Mirrors**
  - Not that fast (response time ~100 μs)
  - Transmittance > 95%
  - Large deflection angles

- **Acousto-optic deflectors (AOD)**
  - Fast (response time ~1,5 μs/mm of laser beam diameter)
  - Transmittance ~ 60 - 85%
  - Limited deflection angle
  - Control of position and trap stiffness

- **Electro-optic deflectors (EOD)**
  - Fast (response time ~1 μs)
  - Transmittance ~ 90%
  - Limited deflection angle
  - High cost

1. ii. What are the techniques employed?

Steerable traps (2):
Holographic Optical Tweezers (HOTs)

Use a spatial light modulator (SLM):
- Simultaneous multiple traps
- Arbitrary shape and size of traps
- Much slower (response time ~10ms).
- 3D manipulation of traps


1. ii. What are the techniques employed?

GPC: Generalized Phase Contrast


1. iii. What are the applications?

**Cell Sorting**

- Flow from sample source
- Catapulting laser beams controlled with intelligent machine vision


**Single Particle as handle: Force Sensing**


**Single Particle as tracer: Viscosity/ Temperature Sensing**

1. iii. What are the applications?

Light Robots (microrobots):
Using multiple handles, it’s possible to create structures with specific functions.

Syringe Function

Cell Manipulation Platform


1. Optical trapping at the microscale
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2. Optical trapping in biological media
   i. Challenges for optical trapping in turbid media
   ii. Wavefront correction algorithms
   iii. Real-time implementation for optical trapping

3. Future perspective & Conclusion
2. i. Challenges for optical trapping in turbid media

- Most Optical Trapping Experiments are done in water

- For a better understanding of biological systems:
  - perform optical trapping in biological media

- However, biological fluids induce additional scattering and absorption:
  - It will reduce the trap stiffness

- Biological media have also:
  - A different viscosity than water
  - Non uniformity
  - Sample to sample variability

2. i. Challenges for optical trapping in turbid media

Random Scattering through biological media:
Spatial Coherence is lost.

Resulting pattern: Volume speckle field, no correlation with the incoming field.

Linearity of the Scattering process:
Algorithm to match the incoming wavefront by inverse diffusion.

Works only using a SLM to correct the incoming beam
phase $\rightarrow$ Holographic Optical Tweezers

Correction phase value $\in [0; 2\pi]$
2. ii. Wavefront correction algorithms

Basic Algorithm principle:
• The SLM is divided in $N$ square segments.
• The Phase is varied from 0 to $2\pi$
• A cost function is evaluated at the output (target)
• After evaluating all segments: Set the corrected phase value

Enhancement: $\eta \equiv \frac{I_N}{\langle I_0 \rangle}$
Intensity over target
Overall average Intensity at the start

Fluid as scattering sample: Speckle pattern will decorrelate after a time $T_p$ (persistence time)

The time to complete one iteration of the algorithm is called $T_i$.

If $NT_i \gg T_p$, the algorithm will not work.

2. ii. Wavefront correction algorithms

Advanced Algorithm: Genetic Algorithm (GA)

Based on species Breeding and Mutation to determine the best correction pattern.

- Generation of Random correction Pattern
- Ranking of the patterns
- Breeding of best ranked patterns
- Add Mutation
- Replace lowest ranked with new offspring

2. ii. Wavefront correction algorithms

Conkey, D. B., Brown, A. N., Caravaca-Aguirre, A. M. & Piestun, R.

![Wavefront correction algorithms diagram]

Algorithms are rated based on the enhancement vs time (or number of iteration)

The GA Algorithm performs better in noisy environments

*GA: Genetic Algorithm  
**CSA: Continuous Sequential Algorithm  
***TM: Transmission Matrix Focusing  
****PA: Partitioning algorithm
**2. iii. Real-time implementation for optical trapping**

Real-time optical manipulation through turbid media was achieved this year.

Peng et al. used an algorithm called Interleaved Segment Correction (ISC). It compromises between noise robustness and convergence speed.

A thin layer of milk was used as a random scattering medium.

Note that the trapped particles are still immersed in water.


Scale bar: 10 μm
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3. Future perspectives & Conclusions
3. Future Perspectives & Conclusions

- Optical Trapping is a powerful and versatile tool, especially for the study of biological systems.

- Most of the optical trapping experiments are done in water (no scattering).

- Holographic optical tweezers and Specific Algorithms allowed for real-time control of structures through turbid media:
  - Enables new possibilities for the study of biological system in real environment.
  - Limited in terms of manipulation speed at the moment.
  - No such structures manipulation in turbid media as been demonstrated so far.

- New Learning Algorithms (machine/deep Learning) might speed up the computations in the future.
Thank you

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DTU Physics

Ada-Ioana Bunea
PostDoc
DTU Nanolab

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National Centre for Nano Fabrication and Characterization

VILLUM FONDEN

BioDelivery Center

novo nordisk fonden
2. iii. Real-time implementation for optical trapping

Interleaved Segment Correction (ISC).


Holographic Optical Traps

- Using an SLM (spatial light modulator):
  - Simultaneous multiple traps
  - arbitrary shape and size of traps
  - Much slower (response time ~10ms).
  - 3D manipulation of traps


1. i. What is optical trapping at the microscale?

Two components: 1) Scattering Force
2) Gradient Force

Ray Optics Regime (particle radius $a \gg \lambda$):
Direct force computation from reflection, refraction and absorption – net momentum change. If $n_p > n_m$, the net force is in the direction of the intensity gradient.

Raleigh Regime (particle radius $a \ll \lambda$):
The particle can be considered as a point dipole.

$$F_{\text{scatt}} = \frac{l_0 \sigma n_m}{c}$$
$$F_{\text{grad}} = \frac{2\pi \alpha}{cn_m^2} \nabla I_0$$

Intermediate Regime (Lorentz-Mie Regime) ($a \sim \lambda$):
More difficult to model. Most interesting applications fall under this regime.

1. ii. What are the techniques employed?

Steerable traps


1. ii. What are the techniques employed?

Scanning technology comparison:
- Galvo
- MEMS
- EOD
- AOD

Table 1. Comparison of scanning technologies for near-infrared wavelength range [14,29].

<table>
<thead>
<tr>
<th>Scanning technology</th>
<th>Galvanometer</th>
<th>AOD</th>
<th>EOD (KTN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max angular deflection speed in 10$^5$ rad/s</td>
<td>0.2</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Max deflection angle in rad</td>
<td>~0.5</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Max aperture in mm</td>
<td>11…30</td>
<td>5…25</td>
<td>0.5…1</td>
</tr>
<tr>
<td>Transmittance</td>
<td>&gt; 95 %</td>
<td>~ 60-85 %</td>
<td>~ 90%</td>
</tr>
<tr>
<td>Response time in μs</td>
<td>200</td>
<td>~1.0</td>
<td>~1.0</td>
</tr>
</tbody>
</table>

1. ii. What are the techniques employed?

Scanning technology comparison:
- Galvo
- MEMS
- EOD
- AOD

<table>
<thead>
<tr>
<th>Scanning technology</th>
<th>Aperture [mm]</th>
<th>Max. deflection angle $\theta$ [rad]</th>
<th>Max. velocity $\dot{\theta}$ [10$^3$ rad/s]</th>
<th>Accuracy $\Delta\theta$ [μrad]</th>
<th>Response time $\tau$ [μs]</th>
<th>Efficiency or Transparency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvo scanner</td>
<td>7…30</td>
<td>0.5…1</td>
<td>~ 0.1</td>
<td>&lt; 2</td>
<td>~ 10$^3$</td>
<td>&gt; 95%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3000…18000)</td>
<td>(0.5…1)</td>
<td>(&lt; 5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polygon scanner</td>
<td>2…12</td>
<td>0.6…1</td>
<td>1…10</td>
<td>~ 200</td>
<td>≥ 10$^3$</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2000…7000)</td>
<td>(5…40)</td>
<td>(~ 120)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezo scanner</td>
<td>10…25</td>
<td>0.01…0.1</td>
<td>0.01…0.1</td>
<td>~ 1</td>
<td>~ 10$^3$</td>
<td>&gt; 95%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(100…1000)</td>
<td>(0.1…1)</td>
<td>(~ 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEMS scanner – static</td>
<td>1…2.5</td>
<td>~ 0.5</td>
<td>0.1…1</td>
<td>n.a.</td>
<td>~ 10$^3$</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(200…1000)</td>
<td>(0.1…1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEMS scanner – resonant</td>
<td>~ 1</td>
<td>0.5…1</td>
<td>10…30</td>
<td>n.a.</td>
<td>≥ 10$^3$</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(500…1000)</td>
<td>(5…20)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EOD (Pockels effect)</td>
<td>2</td>
<td>~ 0.001</td>
<td>2…20</td>
<td>~ 1</td>
<td>0.04…1</td>
<td>&gt; 85%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2)</td>
<td>(3…30)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EOD (Kerr effect, KTN)</td>
<td>0.5</td>
<td>~ 0.2</td>
<td>~ 40</td>
<td>n.a.</td>
<td>~ 10</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(50)</td>
<td>(~ 0.2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AOD</td>
<td>1…10</td>
<td>0.01…0.05</td>
<td>5…250</td>
<td>&lt; 0.1</td>
<td>0.5…15</td>
<td>60%…80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(10…500)</td>
<td>(20…80)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. ii. What are the techniques employed?

Scanning technology comparison:
- Galvo
- MEMS
- EOD
- AOD


Fig. 2. Number and rate of resolvable spots and focal $1/e^2$ beam diameters for $\lambda = 1064$ nm and $T = 1$. 
Displacement Calibration Techniques:

1) Video-based position sensing:

Imaging of the sample plane using a CCD camera. Algorithms for the particle centroid tracking in order to obtain subpixel accuracy.

2) QPD/CCD-base position sensing (forward scattering):

The trapped particle will scatter part of the light. We image the back focal plane of the condenser lens on the QPD/CCD where the light scattered from the particle interferes with the input beam.

Two methods: Fixed particle and piezoelectric stage, or displacement of steerable trap with a know distance from particle.

Fixed particle on a coverslip in sample plane. Recording of the QPD/Camera signal for multiple steps of the piezoelectric stage.

Displacement Calibration Techniques:

2) QPD/CCD-base position sensing (forward scattering):

The signal on the QPD/Camera is given in the following manner:

\[
QPD_x = \int_{x>0} I(x, y) - \int_{x<0} I(x, y)
\]

\[
QPD_y = \int_{y>0} I(x, y) - \int_{y<0} I(x, y)
\]

\[
QPD_z = \int I(x, y)
\]

Fig. 3. Experimental calibration data compared with model response. Solid curve, a silica bead fixed upon a cover slip was moved by a piezoelectric stage through the sensitive range of the detector. Dashed curve, expression (7) with no adjustable parameters besides the nominal sphere size (0.5 \(\mu\)m) and a focus size \((w_0 \approx 0.53 \mu m)\) estimated from the input beam width. The function \(G(x/w_0)\) in expression (7) has a slope of \(w_0^{-1}\) at \(x = 0\) and extrema \(G(x/w_0) = \pm 0.334\) at \(x = \pm 0.552 w_0\).


Displacement Calibration Techniques:

2) QPD/CCD-base position sensing (forward scattering):

The signal on the QPD/Camera is given in the following manner:

\[ QPD_x = \int_{x>0} \int I(x, y) - \int_{x<0} \int I(x, y) \]

\[ QPD_y = \int_{y>0} \int I(x, y) - \int_{y<0} \int I(x, y) \]

\[ QPD_z = \int \int I(x, y) \]

Note that the integrals above should be replaced by finite sums in the case we use a CCD camera.

With this technique, we can also measure the axial position of the particles using a similar calibration.

Trap Stiffness calibration:

1) Active stiffness calibration based on viscous drag force method

We can either:
- Induce known viscous forces on the particle (not fixed) using a piezoelectric stage.
- Force the particle into an oscillatory motion with a steerable trap.

In the first case, the viscous drag experienced by a spherical particle in a moving viscous medium is:

$$F_{\text{drag}} = \beta \cdot v = \frac{6\pi \eta vr}{1 - \frac{9}{16} \left( \frac{r}{h} \right) + \frac{1}{8} \left( \frac{r}{h} \right)^3 - \frac{45}{256} \left( \frac{r}{h} \right)^4 - \frac{1}{16} \left( \frac{r}{h} \right)^5}$$

Where $\beta$ is the drag coefficient, $r$ is the bead radius, $v$ is the fluid velocity and $h$ is the height of the bead from the coverslip. We can then record the particle position and extract the force for small displacement using a linear fit:

$$F = -k \cdot x$$

Where $k$ is the trap stiffness. Once the force sensing is calibrated, we can measure the drag coefficient for different solutions.

Trap Stiffness calibration:

1) Active stiffness calibration based on viscous drag force method

In the second case, we can force the particle into an oscillatory motion using a steerable trap. We get the following equation of motion

\[ m^* \ddot{x} + m^* \beta \dot{x} + (k_{ot} + k)x = k_{ot} A \cos(\omega t) \]

Where \( m^* \) is the effective mass of the particle (includes also the inertia of the liquid around the particle), \( \beta \) is the drag coefficient, \( k_{ot} \) is the trap stiffness, \( k \) is the elastic modulus of the solution, \( A \) is the amplitude of the tweezers motion and \( \omega \) the oscillation frequency.

Knowing \( \beta \), we can obtain \( k_{ot} \) from the phase shift of the particle's motion. Then, once the trap stiffness known, we can measure different solution viscosities.

Trap Stiffness calibration:

2) Passive stiffness, power spectral density method

Brownian motion of particle in an optical trap can be described by the Langevin equation. For fluids with low Reynolds numbers, the power spectrum of the Brownian motion is:

$$S(f) = \frac{K_B T}{\pi^2 \beta (f^2 + f_0^2)}$$

We can measure $f_0$, the roll-off frequency and determine the trap stiffness using:

$$k = 2\pi \beta f_0$$

Where $\beta$ is the hydrodynamic drag coefficient (must be known beforehand).

This method requires that we can acquire data at frequencies between 10 and 50 kHz in order to determine $f_0$. Therefore it can be achieved using a QPD but not usually with a CCD.

Trap Stiffness calibration:

3) Passive stiffness, equipartition theorem method

The equipartition theorem assumes $0.5K_B T$ of thermal energy for each degree of freedom. The energy associated with thermal fluctuations of a particle in an optical trap with stiffness $k_x$ in the $x$ direction is given by $0.5 k_x \langle x^2 \rangle^{-1}$, where $\langle x^2 \rangle$ is the position variance of the particle in the $x$ direction.

The trap stiffness can then be determined using:

$$k_x = K_B T \langle x^2 \rangle^{-1}$$

Using this method, we don’t need know the drag coefficient nor the viscosity of the medium beforehand.

Trap Stiffness calibration:

4) Passive stiffness, Boltzmann statistics method

The particle position histogram is assumed to have a normal distribution resulting from a Gaussian trapping beam. Boltzmann statistics describe the probability density $p(x)$ of the particle position as a function of the optical trap potential $E(x)$:

$$p(x)dx = Ce^{-\frac{E(x)}{k_BT}}$$

Where $C$ is a normalization factor.

We can calculate then the potential $E(x)$ from the histogram and fit it with a quadratic equation to determine the trap stiffness $k_x$:

$$E(x) = \frac{k_x}{2}x^2 + c$$

This method does not require knowing the particle’s shape, drag coefficient or medium viscosity.