ライトフィールドと偏光制御による 3D 光学ピンセット
3D Optical Tweezer based on Light-Field with Polarization Control

○デルネデン　トマ，ブカン　アントニー

○ **Derneden Thomas and Beaucamp Anthony**

慶應義塾大学　理工学部　総合デザイン工学専攻
Department of integrated design engineering, Faculty of Science and Technology, Keio University.
E-mail: beaucamp@sd.keio.ac.jp

This research investigates the feasibility of integrating light-field optical tweezers with polarization-control for 3D micro-manipulation of particle position and orientation. Using a Digital Micro-mirror Device (DMD) and Micro-Lens-Array (MLA), volumetric optical traps are generated. These are then combined with a polarization mask to induce controlled rotation of anisotropic particles. Initial experiments aim to demonstrate stable trapping and polarization-driven rotation, validating the system potential for advanced microscale assembly.

１．Introduction

The manipulation of microscopic particles with high precision is highly valuable in modern optical and material science. First introduced by Ashkin *et al.* [1,2], optical tweezers provide a non-invasive method to trap and manipulate dielectric particles using a highly focused laser beam. They have found applications across a wide range of fields, including in-vitro fertilization (IVF) [3], single-cell biomechanics [4], microfluidic flow control [5] and micro-robotics [6]. This technique relies on the ability of light to transfer momentum to matter, generating optical forces that confine particles near the beam's focal point. Two dominant forces components arise: the scattering force, which pushes the particle along the light propagation axis, and the gradient force, which pulls it toward regions of higher light intensity near the focus.

In the light-field optical tweezers system developed by Le Priol *et al.* [7], that serves as a foundation for this work, optical trapping is modeled under the ray optics regime, which assumes that the particle diameter is significantly larger than the wavelength of the trapping laser (typically in the micrometer range). Under these conditions, the gradient force F_{grad} acting on a dielectric particle can be approximated as:

$$F_{grad} = \frac{2\pi n_m r_{bead}^3}{c}\left(\frac{m^2-1}{m^2+2}\right)\nabla I \tag{1}$$

where r_{bead} is the particle radius, m the relative refractive index between the particle and the surrounding medium, and ∇I the local intensity gradient.

Conventional optical tweezers are generally restricted to a single focal plane and rely on mechanical stages or dynamic beam shaping to reposition the trap, which reduces responsiveness and scalability. To address these limitations, our team developed a compact light-field optical tweezers system that combines a Digital Micro-mirror Device (DMD) with a freeform Micro-Lens Array (MLA), as initially reported in [7]. The DMD controls which portions of the incoming laser beam are reflected toward the MLA by switching micromirrors on or off. The MLA then focuses these selected rays into specific locations within a volumetric workspace, generating multiple optical traps at defined spatial positions as shown in Fig. 1.

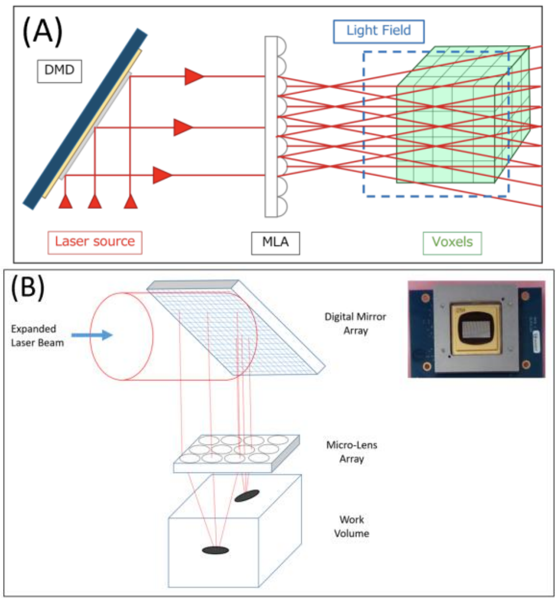

Fig. 1: (A) Light-field trapping concept using the DMD-MLA system. (B) Illustration of particles trapped at different depths within the 3D workspace.

This configuration supports the simultaneous trapping of multiple particles across different focal planes, offering precise volumetric control of particle position. However, it does not account for particle orientation. In certain cases, the ability to control not only position but also angular alignment becomes essential for applications in micro-assembly and targeted manipulation. Prior work by Galajda and Ormos [8] demonstrated that some flat, photopolymerized particles can align themselves with the direction of linearly polarized light. When linearly polarized light interacts with optically anisotropic particles, it exerts a polarization-induced torque. As demonstrated by Simpson *et al.* [10], for small, elongated particles with geometric anisotropy, this torque can be approximated as:

$$\tau(\theta) = A + B\sin(2\theta + \phi) \qquad (2)$$

where θ is the angle between the particle's major axis and the polarization direction, A, B, and ϕ are constants determined by the particle's geometry and optical properties.

Building on this concept, the present work proposes the integration of a polarization mask into the existing light-field optical tweezer system. The goal is to assign a specific polarization direction to each trap, thereby enabling selective orientation of particles within the 3D workspace, in addition to their spatial positioning.

2. Planned Experimental Validation

2. 1. Objective

The goal of this experimental phase is to demonstrate that anisotropic microparticles can be rotated within the 3D volumetric workspace of the light-field optical tweezer system using a globally applied linear polarization. This will serve to validate whether the polarization-induced torque effect, previously shown in 2D configurations by Galajda and Ormos [8], extends to multi-depth trapping conditions.

2. 2. System Overview and Experimental Setup

The developed system consists of a 450nm laser source (Thorlabs L450-P1600MM), 1920×1080 DMD prototyping board (D4100 Explorer), and a custom-made PMMA freeform MLA. Each mirror of the DMD can be toggled between ±12° to reflect incident light toward or away from the MLA. This binary control allows for spatial selection of beamlets which, once passed through the MLA, generate a focused light field as depicted in Fig. 1. By precomputing which DMD pixels contribute to a specific location in the 3D volume, a voxel-mapping matrix is obtained. This matrix directly links DMD pixel activation to focal point formation and can be expressed as:

$$\boldsymbol{S} = \boldsymbol{X} \cdot \boldsymbol{V} \qquad (3)$$

where:

- $\boldsymbol{S}$ is the binary image sent to the DMD (vector of dimension $n \times 1$),
- $\boldsymbol{V}$ is a vector encoding the selected voxel(s) in the 3D volume ($m \times 1$),
- $\boldsymbol{X}$ is the transformation matrix (of size $n \times m$) defining the light-field mapping from DMD pixels to voxel positions.

The matrix $\boldsymbol{X}$ being the light field tensor derived via geometric ray tracing in Anax Hyperion™ (Anax Optics Inc.), associating each mirror on the DMD with every voxel in the working volume. Hence directly linking the desired voxel position to the corresponding DMD pattern as depicted in Fig. 2.

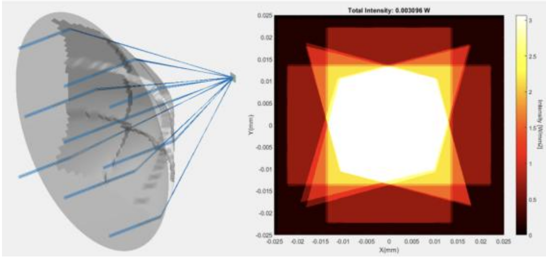

Fig. 2: Light-field trapping concept illustrating the mapping between DMD pixels and target voxels, with discrete beams combining at a trapping point 10 mm away.

The actual implementation of the light-field optical tweezers system is shown in Fig. 3. The 3D workspace consists in a small plastic cell filled with glass beads (diameter 10 microns) suspended in water.

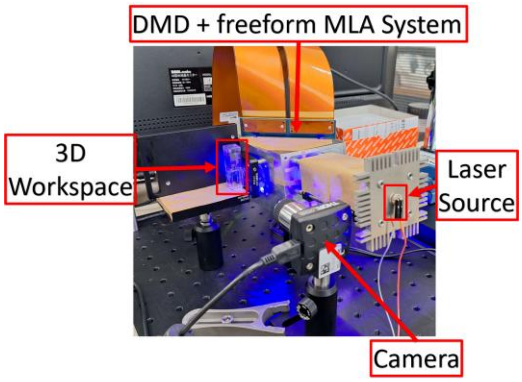

Fig. 3: Experimental setup.

A custom control interface allows the selection and activation of individual voxels within the 3D workspace, while a real-time camera provides a side-view of the resulting light-field focus inside the 3D sample as depicted in Fig. 4.

A simple implementation of polarization control consists in inserting a fixed linear polarizer between the DMD and the MLA. This introduces a uniform polarization direction across the entire light field. By manually rotating the polarizer, we aim to observe corresponding rotation of anisotropic particles (such as flat photopolymerized structures) trapped at various depths within the 3D volume as schematized in Fig. 5. This simplified approach will establish the physical feasibility of polarization-based orientation control before moving to more complex voxel-specific polarization encoding.

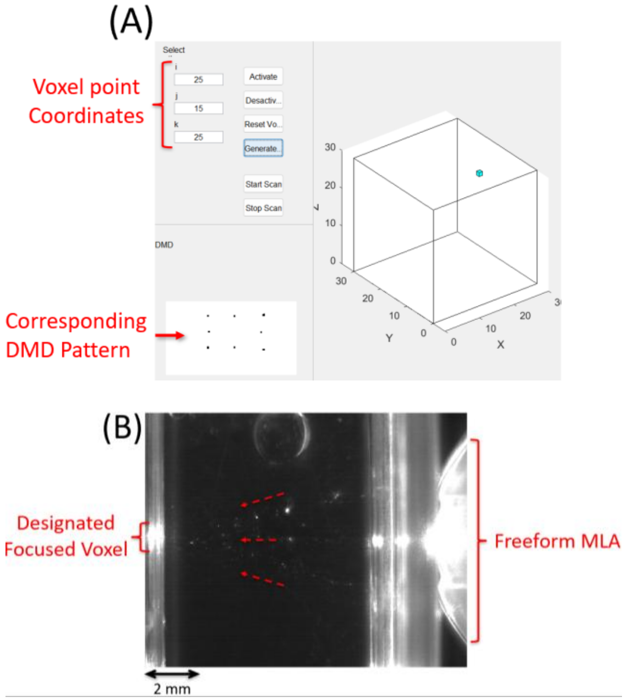

Fig. 4: (A) Software interface for selecting voxel positions in the 3D light-field workspace. Using the inverse matrix formulation described in Section 2, the system computes the corresponding DMD micromirror pattern. (B) Real-time output showing focused rays converging at the target voxel, confirming correct trap formation.

The test particles are flat, photo-polymerized microstructures with cross-like geometries, similar to those used by Galajda and Ormos [8], suspended in either water or a water-glycerol mixture.

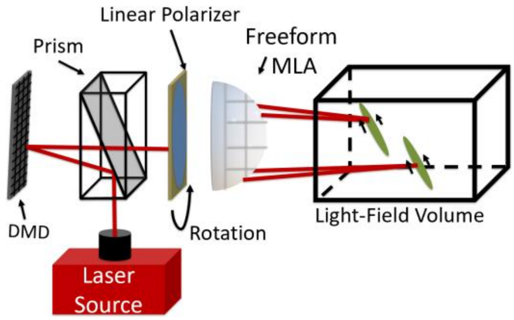

Fig. 5: Setup including a linear polarizer between the DMD and freeform MLA, enabling uniform polarization of trapping rays to induce particle orientation.

2．3．Voxel-Specific Orientation strategy

To address the limitations of using a global polarization direction, we propose integrating a polarization mask into the light-field system, positioned between the DMD and the MLA, as shown in Fig. 6.

Each unit of this mask consists of multiple segments with fixed but distinct linear polarization orientations. When the laser beam reflects off a specific micromirror, it passes through a corresponding mask unit, acquiring a predefined polarization direction before entering the MLA. This way, each voxel (optical trap) not only has a defined spatial position but also a controlled polarization state.

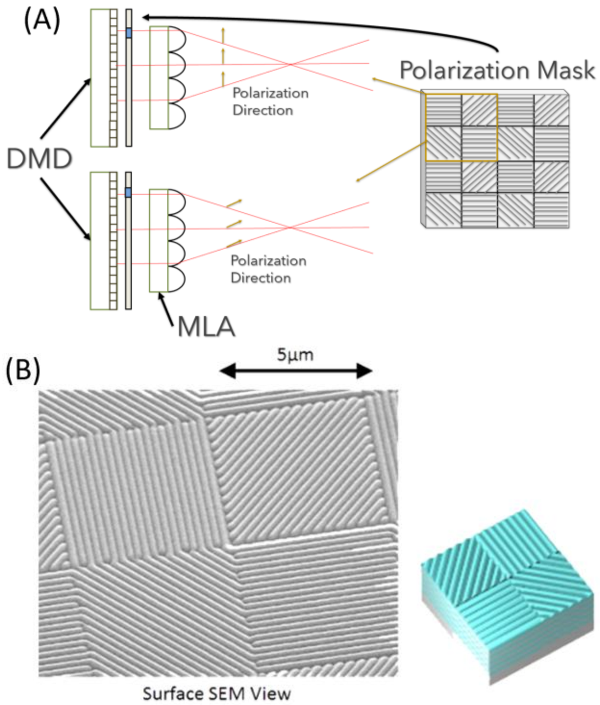

Fig. 6: (A) Schematic of how the mask assigns different polarization directions to each voxel. (B) Surface SEM image (left) and schematic 3D view (right) of a photonic crystal polarization mask [9].

This modification is expected to generate polarization-driven torque on specifically chosen anisotropic particles in the volumetric workspace. With the final goal being the simultaneous and independent control of particle position and orientation.

3．Conclusion and Future Work

This study proposes the integration of polarization-based orientation control into a light-field optical tweezer system to enable full 3D manipulation of anisotropic microparticles. Building upon an existing setup capable of generating multiple independent optical traps in a volumetric workspace, the first step focuses on validating polarization-induced torque using a uniform linear polarization field. While this approach allows rotation only around a single axis, future work will explore strategies for multi-axis control, such as combining multiple polarization sources or advanced optical modulation. Once the principle is validated, a segmented polarization mask will be implemented to allow voxel-specific control of both particle position and orientation. This advancement would open the way for new applications in programmable microstructure assembly, microfluidic systems, and micro-robotic manipulation.

References

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