*Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)*
*15–18 November 2022, Singapore. Edited by* Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-15-0151

# Ultrafast Multi-focus Optical Tweezer based on a Digital Micromirror Device

Yintao Wang[1,*], Bingxu Chen[1,*], and Shih-Chi Chen[1,2,#]

1 Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, N.T., Hong Kong SAR, China
2 Oxford-CityU Centre for Cerebro-Cardiovascular Health Engineering (CoCHE), Hong Kong Science Park, N.T., Hong Kong SAR, China
# Corresponding Author / Email: scchen@mae.cuhk.edu.hk, TEL: +852-3943-4136 , FAX: +852-2603-6002
* These authors contributed equally to this work.

KEYWORDS: Optical tweezer, Ultra-fast wavefront shaping, Digital micromirror device

*Conventional optical tweezers are mostly based on acousto-optic deflectors (AODs) or spatial light modulators (SLMs), which suffer from low spatial or temporal resolution. Accordingly, this limits their use in advanced applications, such as quantitative force measurement, fast particle sorting, and complex 3D micro- or nano-assembly. To address the problem, we present a new optical tweezer system based on binary holography and digital micromirror device (DMD). The DMD-based optical tweezer can operate at 1 kHz in closed-loop mode and 22.7 kHz in open-loop mode, while maintaining the focus resolution and minimal step size close to diffraction limit (i.e., 100s nm). Comparing with conventional systems, the DMD-system has two distinctive advantages: (1) up to 30 laser foci can be simultaneously generated and individually controlled based on binary holography to perform random-access parallel scanning and optical manipulation, where laser scanning is realized via sequentiallydisplaying the synthesize holograms on the DMD. The scanning rate is equivalent to the DMD pattern rate, i.e., 22.7 kHz in our setup; and (2) the binary holograms are synthesized automatically in a highly parallel fashion through custom-developed algorithm in a GPU card, achieving a rate of 8,000 fps, i.e., a 10 to 100 times improvement over CPU-based algorithms. This algorithm enables high-speed closed-loop control of the scanning laser foci at 1 kHz, which may bring opportunities in scientific studies that use optical tweezers. Preliminarily, we have experimentally studied the acceleration, deceleration, dynamic assembling of particles via the DMD system. Theseresults show great potential thatDMD-based optical tweezers can bring high-precision,high-speed applicationsinto play.*

**NOMENCLATURE**

AOD = acousto-optic deflector
BE = beam expander
CW = continuous wave
DMD = digital micromirror device
GPU = graphics processing unit
HWP = halfwaveplate
L = lens
M = high-reflectivity mirror
PBS = polarizing beam splitter
SF = spatial filter
SLM = spatial light modulator

## 1. Introduction

As a powerful non-contact method to manipulate small particles, optical tweezers have been developed and used for various scientific applications for the past 50 years. Atypical optical tweezer system usually consists of a laser source, a scanning unit, a high numerical aperture objective and relateddetecting modules. Among the different system components, the scanning unit is the most important one that determines the speed and performance of the optical tweezer. Different scanning devices, including acousto-optic deflectors (AODs), spatial light modulators (SLMs) etc., have been applied in previously reported systemsto realize spatially tunable multi-focus laser control. Yet, the low precision or the low operating speed limited by the optical components prevent further performance enhancement or new discoveries that require high laser scanning speeds [1].

In this work, we present the application ofa digital micromirror device (DMD) and binary holography to realize an ultrafast optical tweezer. Unlike manyconventional systemsthat usethe DMD as a projection (or reflective) device, we encode designed binary holograms to the DMD to precisely generate and control the amplitudes, phases, and positions of many laser foci simultaneously for 3Drandom-access scanning at the DMD pattern rate, i.e., 22.7 kHz. The holograms displayed on the DMD are generated by a GPU boosted Leeholography algorithm, i.e., GPU-Lee algorithm. This highly linearized algorithm canautomatically generate binary holograms at a >1 kHz speed. Together with the high speed DMD, we have demonstrated new applications,including static control, real-time open-loop and closed-loop control, as well asdynamic self-assembly, at a record-setting speed.

## 2. System setup

The new optical tweezer system uses a DMD(i.e., DLP 4100,0.7" XGA, Texas Instruments) as the scanning component, which generates and control the scanning laser foci via Lee holography [2, 3]. To improve the speed of hologram synthesis for real-time control, we applya GPU-based parallel computing framework. (Details are discussed in the following sections.)

### 2.1 Optical design

Figure1 presents the optical configuration of the DMD-based optical tweezer system, where the laser source is a solid state, Q-switched pulsed laser with a wavelength of 1064 nm (Coherent Matrix-1064) that can also work inthe continuous wave (CW) state for optical tweezer usage.

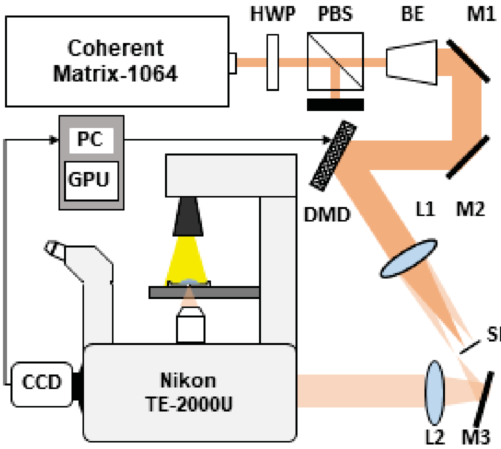


Fig. 1 Optical configuration of the DMD-based optical tweezer

First,to control the laser power, beam diameter, and angle before entering the DMD, atrain of optics, including the half-wave-plate (HWP), polarizing beam splitter (PBS), beam expander (BE) and a pair of mirrors are introduced. After the DMD, a pair of lenses with a spatial filter (SF) form a 4-f system (L1=100mm, L2= 200mm) to spatially select the -1st order diffraction beam, which contains encoded wavefronts for 3D focus control. Finally, the selected laser beam is guided into an inverted microscope (Nikon, Eclipse TE2000-U) and focused on the sample in a Petri dish viaa high numerical aperture (NA) objective (CFI Super Fluor 40X Oil, Nikon). A personal computer (PC) receives and recordsimagescaptured byacharge-coupled device(CCD) camera in real time, calculates the locations of particles,automatically generates binary hologramsby the GPU, and finally loads them to the DMD for fast optical tweezerapplications.

### 2.2Software design

The overall software structureis presentedin Fig. 2, which includes a hardware driver platform with functions of hologram generation, data acquisition, and action execution;as well asa software platform with capabilities of data storage and queuing, strategy selection, and task control. The core of the software setup is the GPU-Lee algorithm written inC/C++ and other partsarebased on Python or LabVIEW (only for FPGA driver).

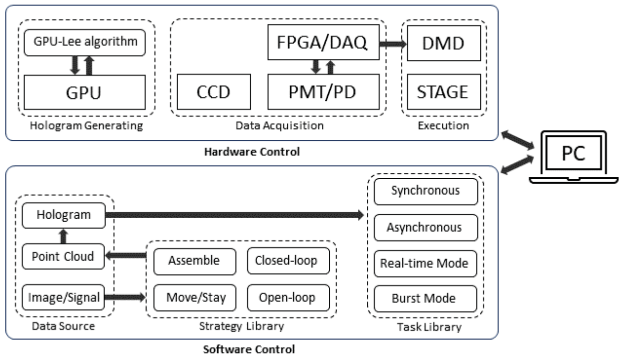


Fig. 2 Software structurefor the DMD-based optical tweezer

In the GPU-Lee algorithm, we can simultaneously execute thousands (depending on the different types of GPU) of calculating threads in a single iteration. Table 1 and Table 2presentthe calculation efficiency of theGPU-Lee algorithm on a NVIDIA RTX3080 for single- and multi-focus generation, respectively. The overallmaximum calculation frame rate canreach >8000 fps/focusfor binary holograms with a size of 1024 × 768.This value has surpassedthe theoretical transfer speed (4.8 Gbit/s) of the USB 3.0port that is used for loading the holograms to the DMD.

Table 1 Time consumedfor single-focus hologram generation

| Frame count | Time expense (ms) | Frame rate (fps) |
|---|---|---|
| 1 | 1.47 | 681.6 |
| 4 | 1.88 | 2131.0 |
| 36 | 6.39 | 5633.4 |
| 100 | 14.87 | 6725.2 |
| 900 | 106.57 | 8445.5 |

Table 2Time consumedfor multi-focus hologram generation

| Foci count | Frame count | Time expense (ms) | Frame rate (fps) |
|---|---|---|---|
| 10 | 64 | 49.47 | 1293.7 |
| 20 | 64 | 91.13 | 702.3 |
| 50 | 64 | 213.62 | 299.6 |
| 100 | 64 | 399.56 | 160.2 |
| 500 | 64 | 1826.19 | 35.0 |

## 3. Results

We have performedmultiple designed optical tweezer applicationsincluding acceleration, deceleration, dynamic assembling of particles via the DMD system. In the all experiments, we used 1-micronsilica spheres as the target particles. The laserpower on the samples was approximately 100 mW.

First, we tested static control of particles as shown in Fig. 3 (A1 and A2). In experiment, the laser focus was modulated and controlled by the DMD (via displaying a designed binary hologram) while the sample stagemoved at a constant speed of 300 µm/s. As can be seen, the microsphere remained in the center of the laser focus during the entire experiment for ~30 seconds, which provesthe efficacy of the DMD system.

Figure 3 B1-B3 and C1-C2,respectively, demonstrated acceleration/deceleration and dynamic assembly. In these experiments, the sample stage was kept static while the laser foci were modulated by the DMD (via sequentially displaying the scanning binary holograms). Specifically, in Fig. 3 B1-B3, we used closed-loop control to accelerate and decelerate the targeted particle. And in Fig. 3 C1-C2, we dynamically assembled three target particles toward the center point in the DMD work field.

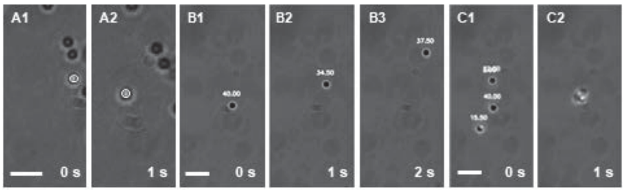


Fig. 3 Demonstrations of static and dynamic particle control via the DMD optical tweezer.A1-A2.static tweezer; B1-B3.acceleration and deceleration; C1-C2.dynamic assembly; scale bar: 5 µm

## 4. Conclusions

We have designed, constructed, and experimentally characterized an ultrafast DMD-based optical tweezer system via binary holography and the custom-developed GPU-Lee algorithm. The hardware and software architecture were designed to meet the requirements of different fast particle-controlapplications. The efficiency and efficacy of the system havebeen preliminarily tested and verified. Moreparticle control and 3D assembly experiments on live cells and will be performedin the near future.

## ACKNOWLEDGEMENT

This work was supported by the Research Grants Council, General Research Fund (14209421); and Science, Technology and Innovation Commission of Shenzhen Municipality (STIC) (No. SGDX20201103095001009).

## REFERENCES

1. Woody, M. S., Capitanio, M., Ostap, E. M., and Goldman, Y. E., "Electro-optic deflectors deliver advantages over acousto-optical deflectors in a high resolution, ultra-fast force-clamp optical trap," Opt. Exp., Vol. 26, No. 9, pp. 11181-11193, 2018.
2. Geng, Q., Wang, D., Chen, P., and Chen, S., "Ultrafast multi-focus 3-D nano-fabrication based on two-photon polymerization," Nature Communications, Vol. 10, pp. 2179, 2019.
3. Geng, Q., Gu, C., Cheng, J., and Chen, S., "Digital micromirror device-based two-photon microscopy for three-dimensional and random-access imaging," Optica, Vol. 4, No. 6, pp. 674-677, 2017.