Assembly of 3-dimensional structures using programmable holographic optical tweezers

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Abstract: The micromanipulation of objects into 3-dimensional geometries within holographic optical tweezers is carried out using modified Gerchberg-Saxton (GS) and direct binary search (DBS) algorithms to produce the hologram designs. The algorithms calculate sequences of phase holograms, which are implemented using a spatial light modulator, to reconfigure the geometries of optical traps in many planes simultaneously. The GS algorithm is able to calculate holograms quickly from the initial, intermediate and final trap positions. In contrast, the DBS algorithm is slower and therefore used to pre-calculate the holograms, which are then displayed in sequence. Assembly of objects in a variety of 3-D configurations is semi-automated, once the traps in their initial positions are loaded.

OCIS Codes: (020.7010) Trapping, (170.4520) Optical confinement and manipulation, (090.1760) Computer holography, (230.6120) Spatial light modulators.

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1. Introduction

Optical tweezers are used for manipulating both single and multiple, micron-sized, particles suspended in solution [1]. Various types of particles can be trapped including transparent silica or polymer spheres, metallic particles and biological specimens [2]. Recent advances in spatial light modulators (SLMs) enable a single laser beam to be split into many beams, enabling the simultaneous trapping of many objects [3]. Such experimental arrangements are termed holographic optical tweezers (HOTs) [4]. The SLM is usually positioned in the Fourier-plane with respect to the sample such that angular deflection of the beam at the SLM gives a lateral translation of the trap, and a change in the wavefront curvature gives an axial shift of the trap. The spatial resolution of the SLM, and the aberrations within the system, limit the maximum displacements to a few 10's µm.

To date, many different algorithms have been applied to design computer-generated holograms for use with HOTs [4-9]. In this work we use both a modified Gerchberg-Saxton (GS) algorithm [9] developed to specify arbitrary geometries of traps in multiple planes, and a direct binary search (DBS) algorithm developed to specify trap positions in continuous 3-dimensional space [10]. We provide examples in which sequences of holograms are used to trap objects initially in simple geometries and then transform their configuration into complicated 3-D structures.

2. Algorithms for designing holograms

In addition to photographic techniques, that produce holograms directly from the light scattered by an object, numerous computer algorithms have been developed to design the hologram pattern required to produce the desired target image [11-12]. Such holograms are called computer-generated holograms. Within optical tweezers, rather than requiring an arbitrary light field, all that is needed is to specify the positions of high intensity within a 3-D volume, which significantly simplifies the computational problem.

The GS algorithm was initially developed to produce a target intensity distribution in one plane [13]. It is based upon the Fourier-transform relationship between the hologram and target planes. Repeated transformation between the planes, accompanied by repeated substitution of the target and input intensities whilst maintaining the phase distribution, gives rapid convergence of the hologram design. By incorporating additional beam-propagation steps into the algorithm, intensities can be specified in multiple planes [7]. However, propagation between the planes requires further Fourier-transform operations, slowing both the iteration cycle and convergence to final hologram design.

Another approach makes random changes to a hologram design. The changes are either kept or discarded depending on whether or not it improves the match between the resulting beam and target intensity distribution, where the latter can be specified in either two or three dimensions. These direct binary search strategies [10,14] are particularly useful because they are not restricted to defining the trap positions on a discrete grid. Further considerations can be targeted, such as positions of zero intensity separating two traps.

3. Hologram display interfaces

We have previously designed holograms to create multiple traps distributed in 3-D, allowing the corresponding structures to be assembled [15]. However, loading the traps in these

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complex structures can be problematic since some of the traps are embedded within the structure, i.e. are surrounded by many other traps. Filling all the traps with only a single object can be difficult and the assembly process may require many attempts. Alternatively, complex 3-D structures can be morphed into such configurations starting from a simply geometry. This requires a sequence of holograms to be designed that gradually transforms the initial simple trap arrangement into the final complex structure.

To facilitate the morphing process, an interface was developed using the LabVIEW programming environment, to display a sequence of holograms. The starting point for both the GS and DBS algorithms is a spreadsheet file specifying the x, y, z positions for all the traps. This can be written explicitly or interpolated from a few key positions. In either case, it is important that the sequential displacement of individual traps does not exceed a fraction of the object diameter, typically 25%. For one, two or three planes, we find that the GS algorithm converges quickly enough using a desktop computer (Pentium4 2x2.8Ghz) to calculate ≈2 holograms per second at a resolution of 512x512. The convergence of the algorithm is improved by the fact that each particular hologram is, itself, used as the starting point for the next hologram in the sequence. For more than a few ten's of traps in more than three planes, the convergence of both the GS and DBS algorithms are too slow for real time calculation. In these cases we pre-calculate sequences of holograms and save them to file. These can then be displayed on the SLM in a real time.

Currently, commercially available SLMs have diffraction efficiencies in the region of 40%. Much of the remaining light appears in the zero order, although some of the incident power also appears in higher diffraction orders. Consequently, all our hologram designs are modified to create the desired configuration of traps typically displaced by 20μm from the zero order. This means that most of the ghost traps produced by unwanted diffraction orders can be blocked by a spatial filter.

4. Experimental arrangement

The optical tweezers are based on a NA1.3, x100, Zeiss Plan Neofluar oil immersion microscope objective used in an inverted geometry. A sample cell was mounted on a 3-axis piezo stage. The trapping laser was a frequency-doubled Nd:YVO_4 laser, with a maximum output power of 1.5 W at 532nm. The laser beam was expanded to slightly over-fill the active area of a Holoeye LC-R 2500 spatial light modulator. The SLM was imaged with a magnification of about 1/3 to fill the pupil plane of the microscope objective. The losses in the optical system coupled with the diffraction efficiency of the SLM results in a laser power in the trapping plane of the order of 100-200mW, distributed between each of the traps.

5. Results

To demonstrate the versatility of the techniques, we show a number of example structures morphed using both the GS and DBS algorithms (Figs. 1-3). For both the GS and DBS algorithms, all holograms were displayed at 512x512 pixels in size, utilising the full resolution of the SLM.

The first sequence of video frames (Fig. 1) shows nine, 2μm diameter, silica spheres morphing into three triangles stacked in planes above each other, separated by 6μm. In this case, once the structure is assembled, the hologram sequence is reversed to return the line configuration. The ability to return to this starting configuration proves that the traps remain distinct throughout the manipulation despite periods where one object is immediately in line with another, along the optic axis. The holograms were derived using the multi-plane GS algorithm to calculate holograms in real time, as determined from the spreadsheet file specifying the trap trajectories.

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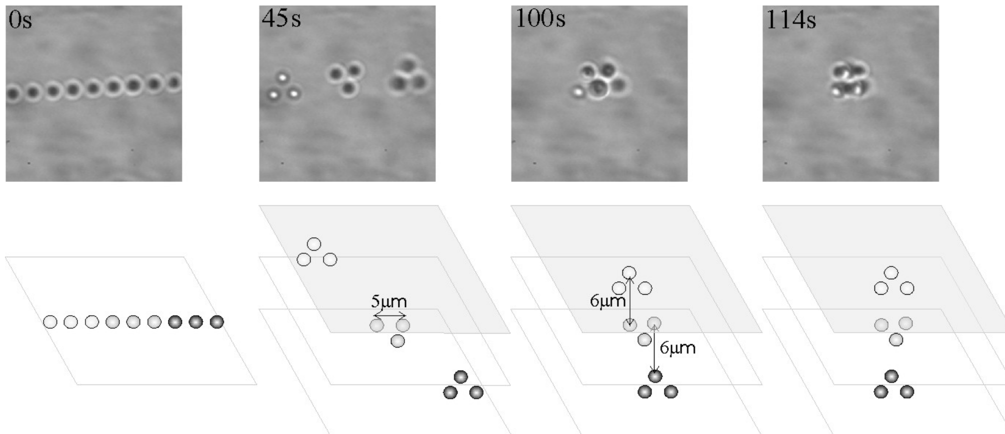

Fig. 1. [2.3MB] Sequence of video frames showing nine 2µm silica spheres morphed to form three triangles with 5µm side lengths stacked in three planes, with 6µm between planes. The times at which each frame was taken is shown in the top corner.

The second sequence of video frames (Fig. 2) shows an initial geometry of three lines of nine 1µm diameter silica spheres manipulated into three grids of nine spheres and each layer separated axially by 8µm. This geometry of spheres would be particularly difficult to trap by filling each trap from a static hologram since the central trap in the middle layer is completely surrounded by other traps. By automating the manipulation process, the user only loads the initial arrangement of traps. Again the ability to reverse the sequence shows that the individual traps remain distinct despite being in close proximity to each other both laterally and axially. Note, during the morphing sequence the sample stage was translated in respect to the traps. The translation shows the individual traps are robust enough to maintain their integrity against the resulting Stokes drag force.

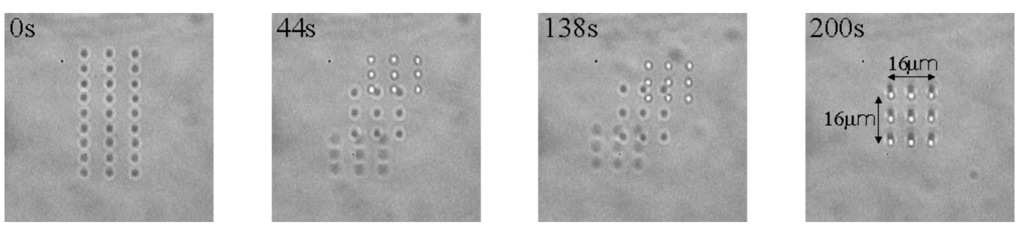

Fig. 2. [0.85MB] Sequence of video frames showing twenty-seven 1µm silica spheres initially trapped in three lines of nine spheres and morphed to form three grids of 3 by 3 in three different planes, separated by 8µm. The times at which each frame was taken is shown in the top corner.

The third sequence of frames (Fig. 3) shows eighteen 1µm diameter silica spheres, initially positioned in two lines, and then morphed into a configuration corresponding to the unit cell of a diamond lattice. In the initial orientation with the [100] direction parallel to the optical axis, this configuration comprises five separate planes. The assembly sequence of holograms was pre-calculated using the DBS algorithm. An additional sequence of holograms rotates the unit cell by 360 degrees, about a high crystal-index axis before reversing the procedure, returning to the original dual-line configuration. In the rotation phase we are effectively calculating trap positions in up to 18 different planes. Using the GS algorithm, we were unable to reproduce this manipulation and in addition, the large number of planes in the rotation stage results in a slow iteration of the GS algorithm.

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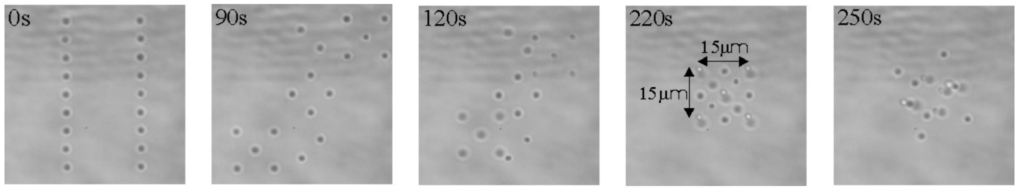

Fig. 3. [2.6MB] Sequence of video frames showing the morphing of 15µm diamond unit cell made from eighteen 1µm silica spheres. The whole sequence took 5 minutes to complete.

The final frame sequence (Fig. 4) shows a similar geometry of trapped spheres to the diamond unit cell (Fig. 3), except four 1µm silica spheres are replaced with 2µm spheres to give a mixed unit cell corresponding to a zincblende structure. Again the formation of the structure in five planes is followed by a rotation about a high order axis. The holograms were pre-calculated using the DBS algorithm.

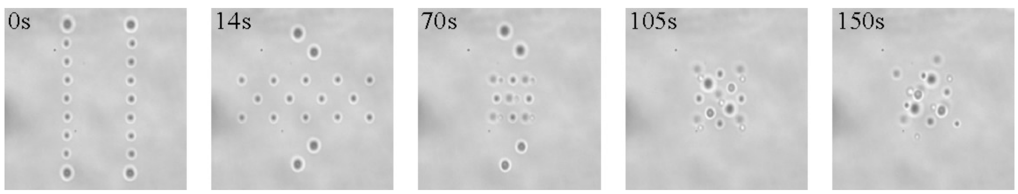

Fig. 4. [2.2MB] Sequence of video frames showing the morphing of a 15µm zincblendee unit cell made from fourteen 1µm and four 2µm silica spheres. The whole sequence took 5 minutes to complete.

6. Discussion

The methods used to calculate the hologram patterns reflect the different strengths and weaknesses of the design algorithms. The GS algorithm converges fast enough for holograms to be displayed in real-time on the SLM, although its main limitation is that it slows with increasing numbers of planes (making, for example, rotation of a multi-plane 3-D structure around arbitrary axes problematic). The DBS algorithm is slower than the GS algorithm, preventing it from being used interactively. However, the DBS algorithm allows control of the intensity in an arbitrary number of planes, making it more suited for the generation of more complex structures.

All the examples we show within this work involve sequences of holograms, displayed over many tens of seconds, to assemble structures with dimensions of tens of microns. The time required for the manipulation of the particles corresponds to speeds of up to 1 micron per second and is limited by a number of factors. As each hologram corresponds to a discrete pattern of traps, individual movements of each trap between successive holograms must not exceed the capture range of the trap. We restrict these steps to be a maximum of 0.5µm. When using the GS algorithm for the real time calculation of holograms, this limits the update rate to 2 holograms per second, hence the observed movement rates. For pre-calculated holograms, we are in principle limited only by the update rate of the SLM, which is in the region of 10Hz for the SLM used in our experiments. However we find that we are still limited to similar movement rates. Additional factors limiting the maximum translation speeds of individual traps in a complex 3-D structure are degradation of the trap quality due to aberrations in the optical systems, scattering from neighbouring objects within the structure and reduced contrast in the trapping light field.

7. Conclusion

We show particles initially trapped in lines can be manipulated into 3-D geometries using sequences of holograms. The holograms can be calculated in real-time using a Gerchberg-Saxton algorithm or pre-calculated using a direct binary search algorithm. The use of

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hologram sequences means that multiple objects can be loaded into traps whilst arranged in a single plane, and then subsequently transformed into the chosen geometry. For both algorithms we observe that two objects within a structure can be displaced both laterally and axially with respect to each other. The ability to displace two objects in the axial direction is, at first sight, surprising since one might think that traps further away would be degraded by the shadow of those positioned between them and the objective lens. However, this is not the case since the high NA of the trapping beams means that the obscuration of one trap by another is minimised.

In addition to the intrinsic excitement of forming microscopic 3-D structures, we believe that such structures will have applications in measuring mechanical properties of materials, photonic and biological crystal growth, tissue engineering, permanent extended 3-D structures, and manipulation within microfluidic devices. Some of these latter applications are aided by the fact that 3-D structures formed within optical tweezers can be made permanent by using a gel solution in which to trap the objects which are then locked in place when the gel sets [16].