Arbitrary multi-beam laser scanning and trapping by use of a spatial light modulator and manual scripting interface

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ABSTRACT

A multi-beam, variable footprint, laser beam steering and shaping system is described and used with a microscope to demonstrate multi-particle laser trapping. It is built around a computer-interfaced 512x512 pixel analog phase-only spatial light modulator (SLM) and a 1 W, 1064 nm wavelength laser. Hand sketches on paper made with a digital pen are used to prescribe the footprints, velocities and trajectories of multiple, independently-controlled diffracted spots. Continuous scanning is approximated by automatically designing a sequence of phase-patterns that are run through and diffracted by the SLM. Very complex scanning sequences of dozens of independently controlled spots can be quickly designed and run. The number of beams that we can trap with is necessarily limited due to the low throughput (~23 mW) of the IR light through the microscope optics. Among the trapping experiments done with the system a triangular shaped vortex ring tends to stop single particles at the apexes of the triangle. However, collision with a second particle pushes the first particle past the apex and sets it into motion, leaving the second particle stopped until collision with a third particle. The discrete motion conditioned on collisions is suggestive of a queuing process or a Markov chain.

Keywords: Spatial light modulators, laser trapping, man-machine interface

1. INTRODUCTION

Spatial light modulators can be programmed to produce an essentially infinite number of laser patterns. This arbitrariness is certainly apparent for SLM's that are imaged onto the sample; e.g., the phase contrast imaging and laser trapping system of Rodrigo *et al.*[1,2] Here there is a one-to-one mapping between the SLM plane and the sample plane. For systems where the SLM phase modulation is Fourier transformed to the sample plane, there are many desirable features; e.g. increased optical power density, variable focus depths, and complex-valued diffraction patterns (e.g. vortex beams). However, Fourier design requires increased computational load, compared to one-to-one mapping. Furthermore the development of a software interface for human control of the system is perhaps more involved, as well.

For some time our group has been concerned with applications of diffractive SLM's to real-time problems;[3-6] e.g., the rapidly evolving visual environments of robotic assembly lines, automated battlefields, colloidal particles viewed under a microscope. In order to make a convincing case for the usefulness of the systems we must be able to demonstrate the capabilities that SLM-based beam formers can be programmed to produce (a) a wide range of patterns, (b) at or near real-time rates, and (c) with limited programming effort by the casual user, or (d) autonomously, in possibly (e) a visual environment for which there is little a priori information.

In this report we present our most recent efforts at demonstrating the programmability of diffractive SLM's. We report on improvements on our manual scripting interface that was first reported in Ref. 3. We also report on a system that to a limited degree can self-program and project laser patterns based on active and passive imaging of the scene. We are working towards a multi-object tracking system that will maintain laser spots on moving objects. While a multi-object image tracking software module has been developed for us by our collaborator L. G. Hassebrook, U. Kentucky, we have not completed the integration of this module with our laser pattern generating software. We also report operator initiation of laser trapping of micro-beads, which are then automatically translated under computer control.

With further improvements in integrating the tracking module, together with speed ups to the computer code we anticipate that it will be possible to identify and track moving particles, trap the particles, and then guide them while continuing to verify the presence of the beads in the trap. These efforts at demonstrating user-friendly interfaces for programming complex dynamically changing sequences of diffraction patterns, are intended to help potential application end users evaluate what might be practically possible, and to give systems engineers the ability to rapidly develop test scenarios for evaluating system performance and developing system specifications for a final design of a system. Given the limited state of development of programmable Fourier transform systems, it is certainly of a critical value to have such a prototyping tool for evaluation purposes. Once the software system is developed to satisfactory levels then significant effort would need to be devoted to finalizing the code and optimizing it for speed. Note that currently the software is based in Labview, and as a result, the speed of pattern generation is significantly limited — by the overhead of Labview, rather than the computational power of current day personal computers. On-line design times in Labview can require from a few tenths to several seconds per frame depending on the particular design algorithms used.

2. THE SLM AND ITS DIFFRACTION PATTERNS

Two model 512N15 (Boulder Nonlinear Systems, Inc, Lafayette CO) reflective SLM's each with 512×512 square pixels on a pitch of 15 μm are used in this study.[7] One is coated for 533 nm and the other used for laser trapping is coated for 1064, with the parallel aligned liquid crystal layer thicknesses chosen accordingly. The SLM's are addressed with 128 grayscale levels, though a linear 2π range is from 20-25 graylevels depending on location across the device. These SLM's have been calibrated to correct for spatial nonuniformity and the varying phase vs. address voltage response across the device.[8] The typical setup for display of a 532 nm, 5 mW laser uses either a beam splitter (see figure in Ref. 3) for display directly on a camera, or a slightly off-axis illumination for visual display of the diffraction patterns. The laser trapping microscope also uses off-axis illumination to eliminate beam splitter loss from the SLM (Fig. 1)

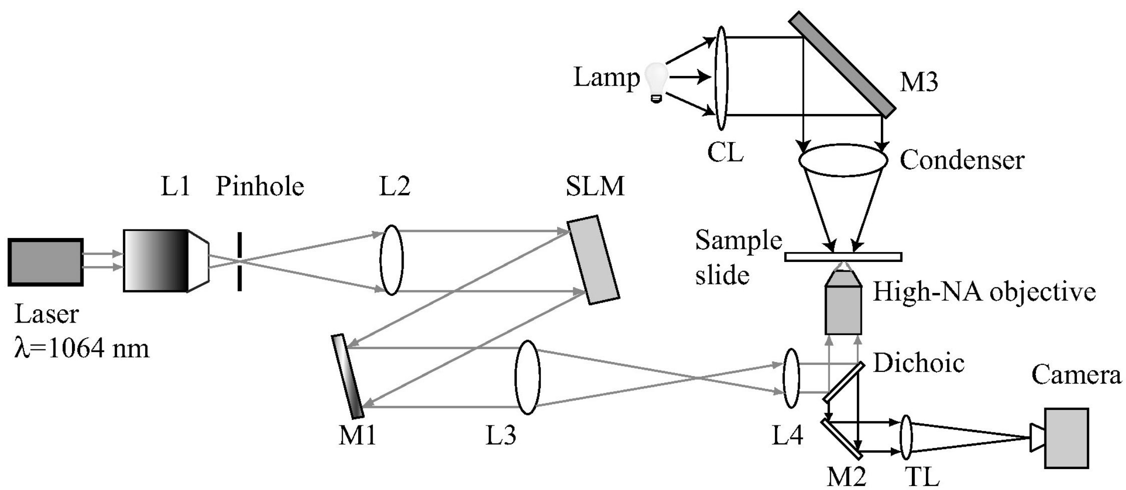

Fig. 1 Configuration of the laser trapping system. The microscope is an IX71 inverted scope, which is represented schematically.

The large number of pixels (256K) and full 2π range suggest that the SLM can produce intricate patterns with image quality approaching that of fixed pattern diffractive optical elements (DOE) and computer generated kinoforms (CGH). We demonstrate this with two sets of patterns produced using a modified iterative Fourier transform algorithm (mIFT) that can produce nearly uniform intensity spot array patterns (Fig. 2).[9] In order to help users of the SLM better appreciate the modified mIFT algorithm, the user can select to view the theoretically calculated diffraction efficiency η and the peak-to-peak nonuniformity U, in alternating frames of the diffraction pattern (Fig. 3). This is convenient in that it enables the user to see iterations directly on the viewing screen without repeatedly turning to view the monitor.

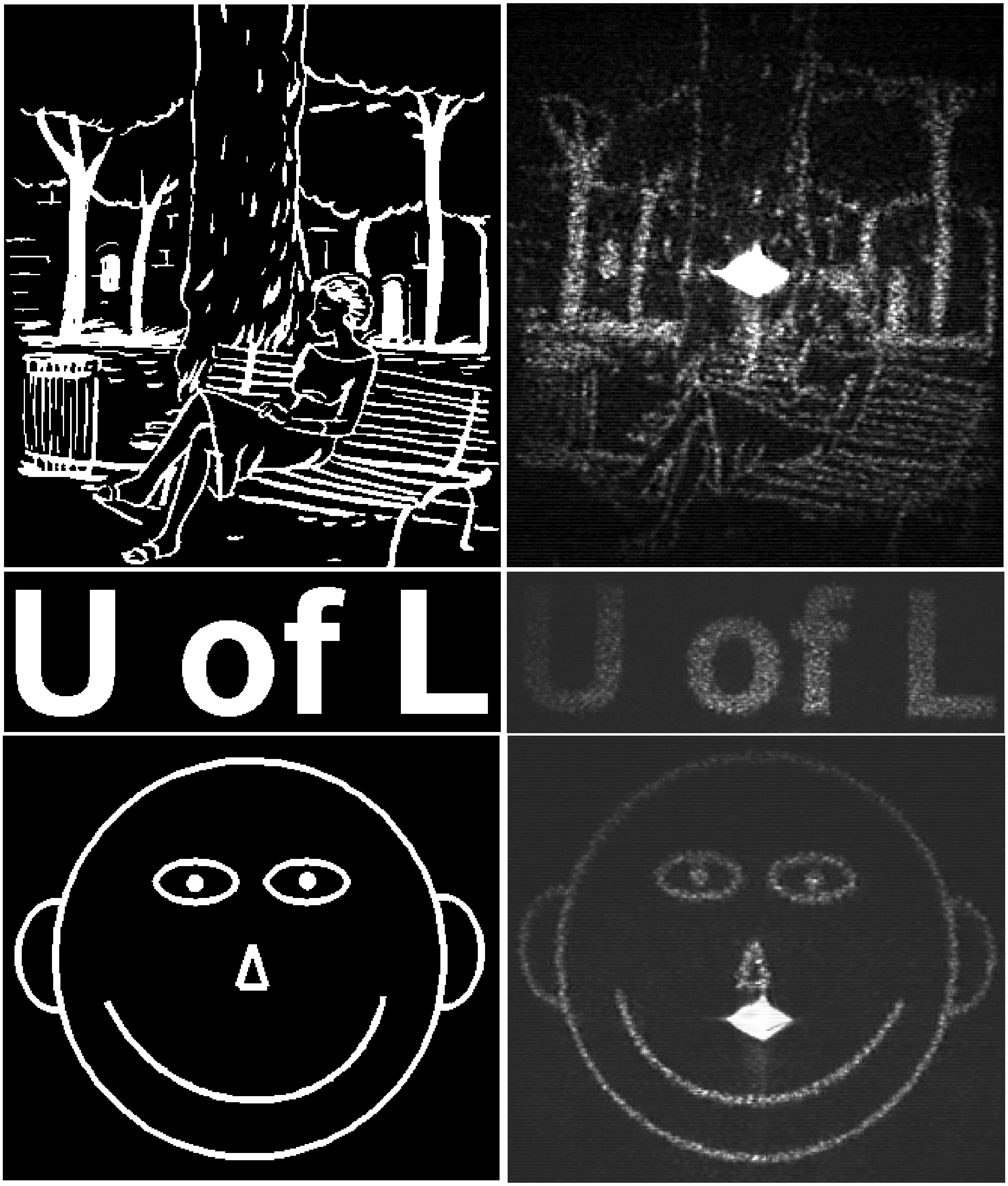

Fig. 2. Input images for design (on left), and resulting 533 nm laser patterns (on right). The images show intensity rolloff as would be expected for an SLM with ~85 % fill factor.[4] The center image is above the optical axis, and the top and bottom images are centered on the optical axis. The bright spot is due to unmodulated light that is reflected from the SLM without passing through the liquid crystal. It is broader than the diffraction limit, because it is out of focus and distorted due to curvature of the SLM. The curvature is corrected by the SLM calibration programming for the diffraction pattern, but not corrected for the unmodulated light.

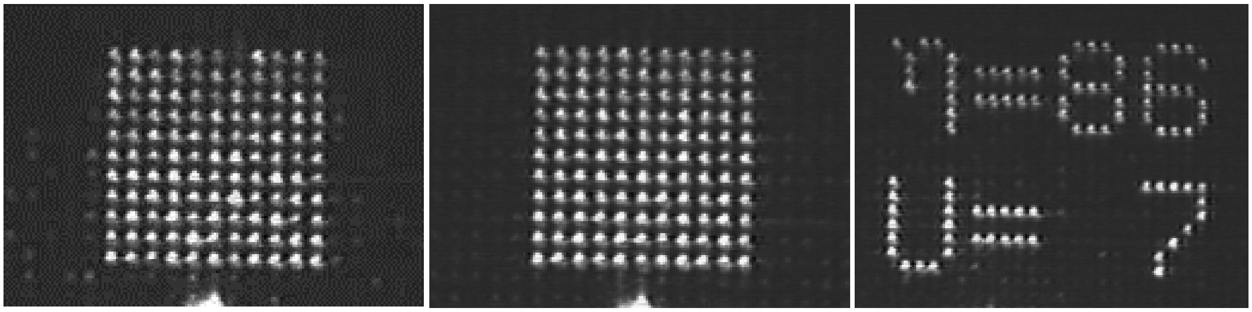

Fig. 3. Diffraction patterns of early and later iterations of the mIFT of an 11×11 array of spots. The early image has a larger background of noise spots. The on-axis spot from unmodulated light is evident under each array. The rightmost image is a projected diffraction pattern formed between iterations of the spot array design that reports efficiency and nonuniformity.

One approach on the path to demonstrating automated real-time tracking and active illumination[7] is to be able to project a pattern on an object in a scene that is captured in video. Our system is capable of projecting an outline directly on an object viewed in the scene. In a three-dimensional environment this is non-trivial. Even if the projection is onto a plane in three-dimensional space, calibration is required to map the captured image to the projected diffraction pattern. We accomplish this for an off-axis SLM and camera by first projecting a pattern (typically the spot array in Fig. 3), measuring the (linear) distortion in the captured image, and then predistorting the DOE design accordingly. In our examples we project the outline of the object back on itself. The outline is defined using a Sobel filter. Fig. 4 shows two sets of objects as viewed by the camera and the resulting object outlines. The objects have been removed from the field for improved viewing of the diffraction patterns, but the mapping is essentially perfect as long as the object is close to the calibration plane. The program allows the user to select the projection of a continuous outline or (as shown for the 3.5" disk) the outline can be sampled. Sampling is used to focus more of the laser light into a smaller bandwidth thereby increasing the brightness and fidelity of the diffraction pattern.

Another way to demonstrate the diffractive system concepts is through the use of a graphical users interface. A digital pen is used to record the identical user strokes that are written by the ink pen in the tip of the digital pen. The vector file can be time sequentially interpreted to identify breaks in writing and spot properties (size, shape, velocity) which are selected from palette buttons on a paper programming template. (See Ref. 3 for an image of the pen template and more on the programming and software interface.) Fig. 5 shows a digital image of hand writing captured from the pen. The text was written in three passes, and between each pass, another shape was selected for following the trajectory of the handwriting. In order to make even clearer to the user how the pen data is being interpreted, an option can be selected to diffract a faint diffraction pattern of the entire trajectory (center panel of Fig. 5).

3. MULTISPOT LASER TRAPPING DEMONSTRATIONS

Using the laser trapping system in Fig. 1 with a 40X objective we trap 1.1 µm polystyrene beads (Fig. 6) in a triangular vortex beam from the SLM (lower right Fig. 6). The vortex beam, because of its spiral phase causes the particles to move around the vortex in the counterclockwise direction. Beads tend to pile up at the kinks in the pattern. This is particularly interesting when one or two beads pile up, then another bead collides and knocks one bead free. The motion (other than the increasing number of beads, is periodic. Each row of Fig. 6 shows a cycle of repetitive motion. The black arrows locate the two beads at the lower right corner. One bead knocks free of another bead which was initially piled up. Besides the collision shown in the pictures, in movies it is also clear that a single bead is trapped at the top of the vortex, and the second bead pushes the first bead free, with the second bead now trapped. The motion is reminiscent of a Markovian state model or cellular automata. It would be interesting to further consider the range of optical power and spatial distributions that enable the discrete motions to be continued, and the degree to which reliable and repetitive queuing chains can be produced.

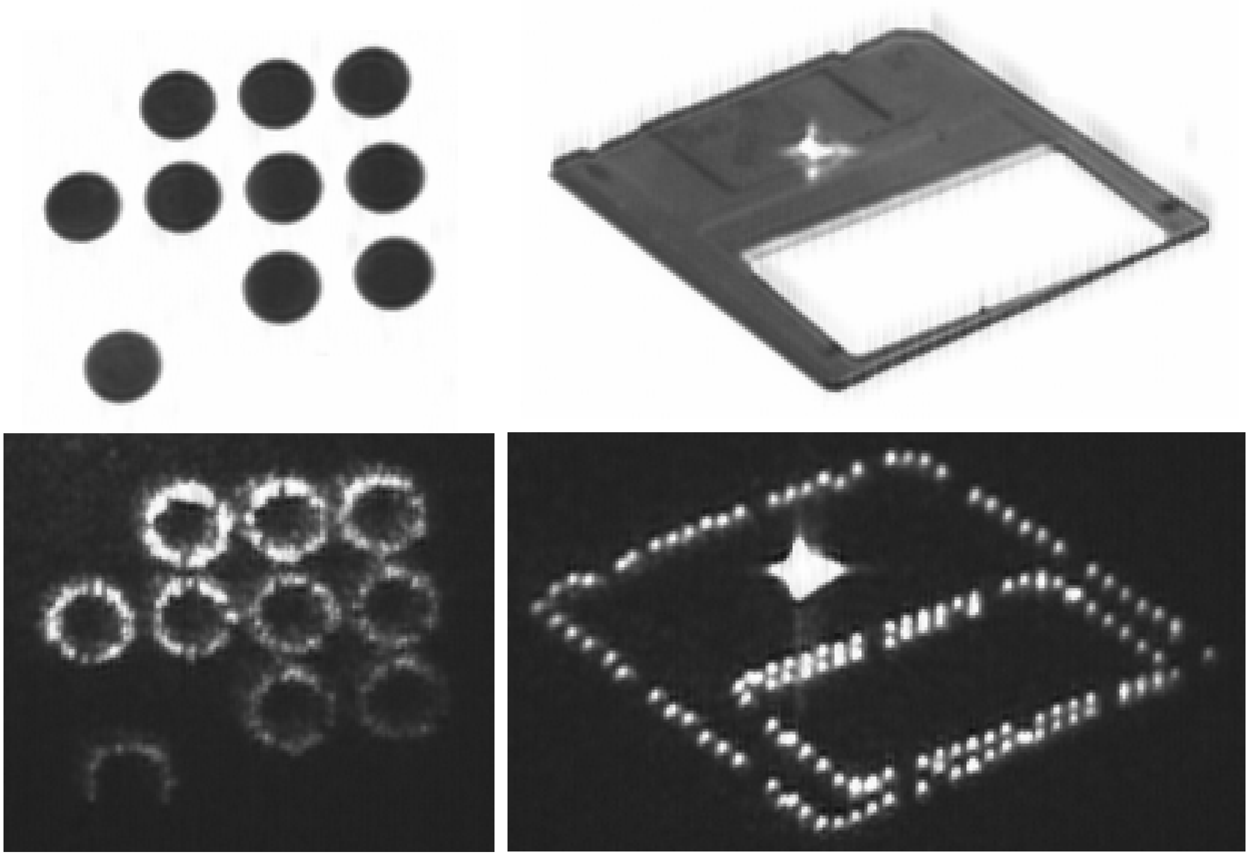

Fig. 4. Video images recorded by camera (top) and corresponding images of the laser outlines of the objects produced by programming of the SLM (bottom).

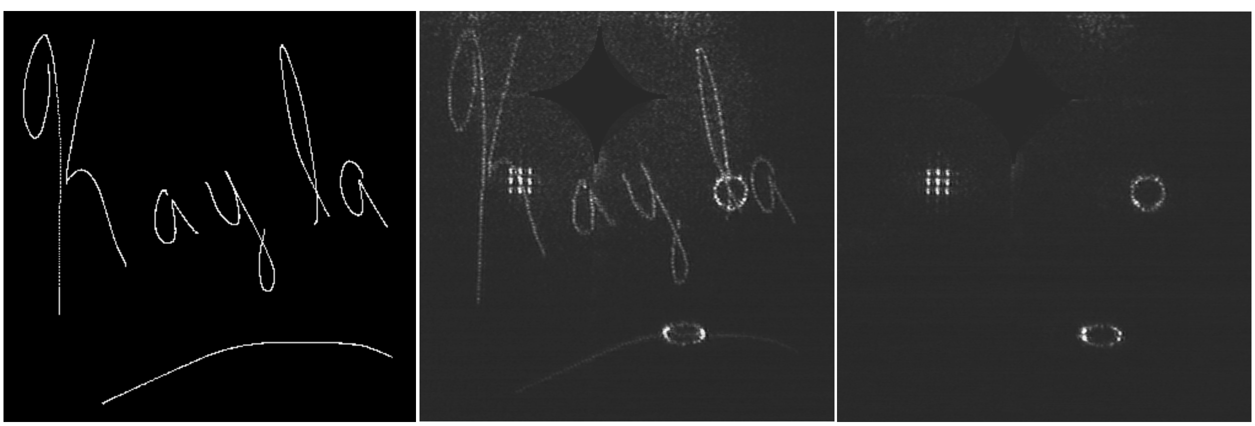

Fig. 5. The left panel shows the desired trajectory digitized from the pen file. The middle image shows the three patterns on the three trajectories “Kay”, “la” and the underline. The right panel shows the three patterns at the same point on the trajectory as the middle image. The diffractions patterns have a diamond shaped stop that blocks the on-axis spot.

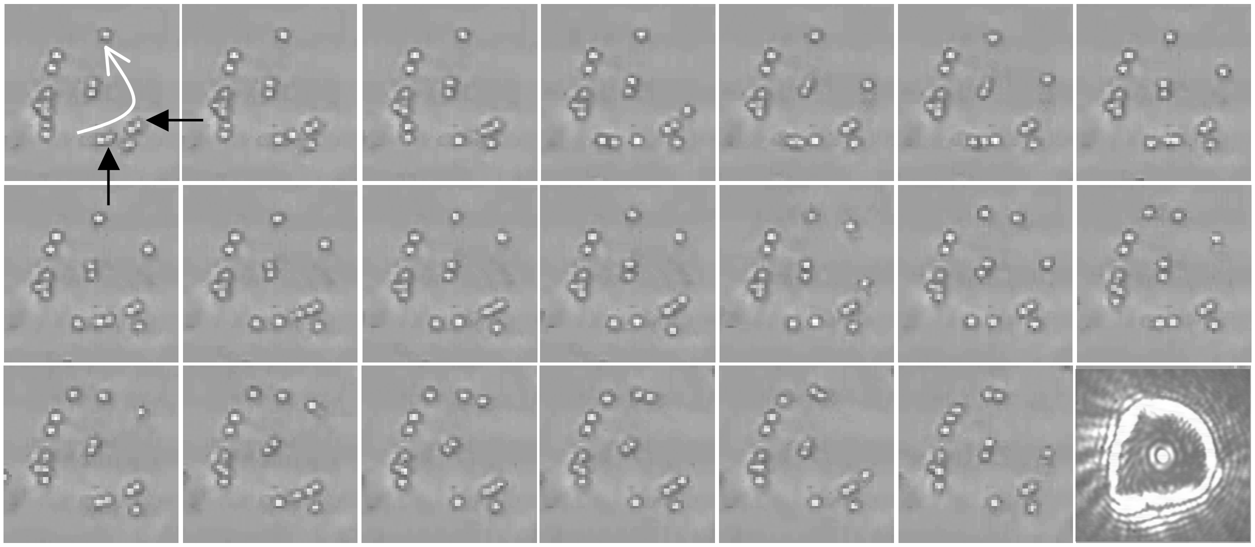

Fig. 6. Repetitive discrete state motion of beads in a triangular trap. Beads tend to pile up at the corners of the vortex beam (lower right) and a collision of one bead with one or two stopped beads is needed to set a bead into motion. A similar motion is observed in each of three successive rows.

As a final example of the type of demonstrations, we have been working towards automated tracking and trapping of beads, once they are identified by the vision tracking software and after they are trapped and being translated. Currently we designate a few (so far up to three) beads by mouse control. Then three spots are generated in time sequence. A velocity of the spot trajectory is chosen to as fast as possible without losing the bead from the trap. Visual tracking will enable us to more closely determine when the maximum bead velocity is exceeded. For these experiments the speedup of the liquid crystal switching is essential to achieving maximum speed. An additional correction (initial overshoot of the addressing voltage) will be used to speed up the switching speed of the SLM from a few hundred ms per frame to under 50 ms per frame.[10]

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