First High Speed Simultaneous Force Feedback for Multi-trap Optical Tweezers

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***Abstract*— Optical tweezers use a tightly focused laser beam to trap dielectric micro-object. Haptic optical tweezers integrate a robotic haptic device into the system to control trap positions and in the meantime feedback forces. This technique opens a broad reaching applications by providing direct and intuitive interactions during micromanipulation. However, 1 kHz sampling rate is required to ensure a reliable tactile sensation. A system satisfying this requirement has been presented in our previous work. This paper goes one big step further to perform real-time high speed haptic feedback on multi-trap optical tweezers. The goal of the system is to enable users to touch the microscale object the same way as using their fingers. The used force sensor is a novel event-based vision sensor that transmits output as a stream of asynchronous timestamped events that eliminates internally the redundant static information. The associated event based algorithm can thus be able to track the positions of two spheres up to 1 kHz. A contact experiment is performed demonstrating the feasibility and the efficiency of the presented method. To our knowledge, this is the first time high speed haptic feedback is performed on multiple microspheres simultaneously in a contact scenario.**

I. Introduction

Micromanipulation and microassembly tasks can be accomplished using different approaches [1][2][3]. Optical tweezers are such an advanced tool for micromanipulation and microscale force measurement [4][5][6][7]. The optical force generated by laser's electromagnetic field focused by a high numerical aperture microscope can produce stable trapping of dielectric objects. Silicon or polystyrene micro-beads are often used either as a "handle" to indirectly manipulate the desired target or as a force "probe" to touch other objects to study biological or medical functions at microscale [8].

Force feedback teleoperation is an advanced approach to perform micromanipulation [9]. Force feedback high resolution teleoperation has assisted users in performing tasks that are either impossible or with high failure rate [10][11][12]. The ideal sampling frequency of haptic devices attains to 1 kHz to ensure a realistic tactile sensation[13][14].

Vision is a typical way of force measurement in optical tweezers. Conventional image processing techniques cannot provide a plausible solution that tracks the positions of microspheres at 1 kHz in a complex micromanipulation environment [15]. The asynchronous vision sensor, which mimics biological retinas and reacts to temporal contrast, has been successfully used to track at high speed the position of microspheres [16]. Promising result has been obtained in [17], in which users have succeeded in exploring a complex three dimensional target surface and feeling the high quality haptic feedback in real-time.

Multiple optical traps significantly enhance the capability of optical tweezers. Coupled with parallel haptic devices, the system will be able to control multiple microspheres simultaneously, and more importantly, to feel the interaction forces on multiple points. Each probe acts like an independent finger. The ultra-flexibility and dexterity of such system will surely enhance the human capability in complex micromanipulation and microassembly tasks.

To achieve this capability, space multiplexing or time multiplexing methods are possible. Spatial Light Modulator (SLM) is a computer-controlled diffractive optical element that is able to modulate the phase of the laser by generating holograms. It allows space sharing of power to trap maximally a few hundred beads simultaneously in three dimensional space. Recent progress in parallel computing made it possible to generate holograms in real-time using graphics processing units (GPU)[18]. However, the bandwidth of such system is limited in the order of 200Hz [19].

Time multiplexing can be realized by an Acousto-Optic Deflector (AOD) or a galvanometer scanning mirror system. Unlike AOD, the galvanometer is an optically bilateral system. The vision sensor, if placed correctly, can have the laser spot constantly fixed in the scene. In this paper, we adopt the approach of galvanometer time-sharing so that the laser position can be freely controlled and is always fixed in the camera view.

In this paper, we present a system that can perform high speed force measurement on multiple optical traps. An asynchronous event based vision sensor and the associated event based algorithm are used to track simultaneously two microspheres. This is the first time, to our knowledge, that real-time force feedback can be performed on multi-trap optical tweezers in a complex contact scenario.

The paper is organized as follows: The system design and the experimental set up are presented in Section II. Our previous system will be briefly introduced firstly and our new setup will be presented and compared in a second stage. The experimental results are presented in Section III and Section IV concludes the paper.

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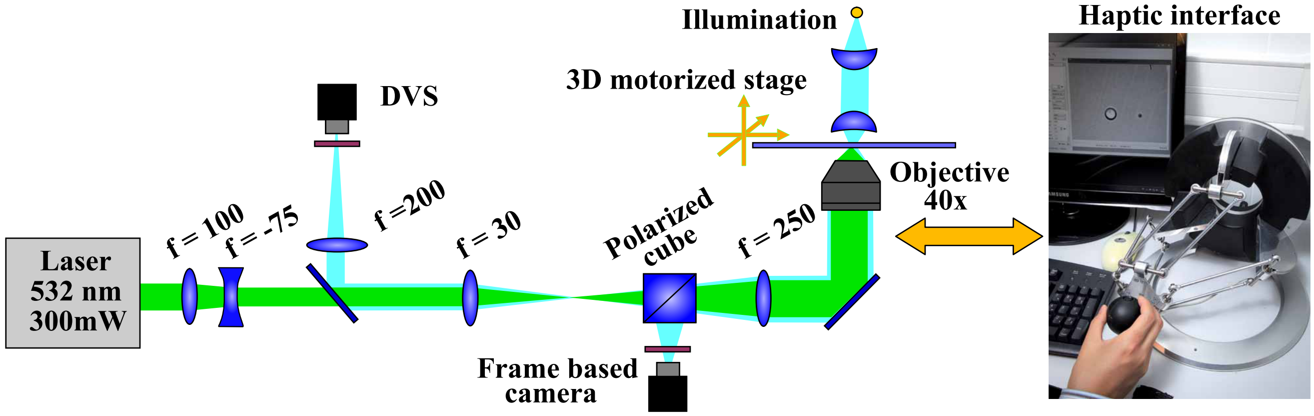

Fig. 1. (a) A schematic representation of the optical system. (b) Haptic interface - the master device for teleoperation.

II. High speed haptic optical tweezers

A. The single trap haptic optical tweezers

Optical tweezers is a tightly focused laser beam that is able to trap micro-sized dielectric object with pico-newton level forces. This technique is advantageously contactless. A haptic optical tweezers takes into account the operator in the loop by including haptic feedback in the design so the system is capable of truly interacting with the microworld.

A single trap haptic optical tweezers has been developed in our previous work. The setup is as follows: Fig.1 (a) shows a schematic representation of the optical setup. The system is composed of conventional optical tweezers : laser source (532nm, 300mW) and oil-immersion high numerical aperture objective (Olympus UPlanFLN 40x, NA 1.3). A laser trap is generated and remains fixed in our configuration. The force estimation is obtained according to a trap stiffness model by measuring the relative position of the object with respect to the laser spot. A fast CMOS digital camera of 659×494 pixels (Basler Scout series) allows the observation of the scene. A prototype of the asynchronous event based vision sensor, called Dynamic Vision Sensor (DVS) [20] is used for force measurement.

A haptic interface (Omega, Force dimension), see Fig.1 (b), is coupled to a three dimensional motorized micromanipulator composed of two microstages for xy-axes (PI, M126.CG) and a nanostage for z-axis (PI, P528.ZCD) to adapt to different precision requirements on different axes. During teleoperation, the user moves the master device – the haptic interface to control the slave device – the micro/nano stage to generate displacements. The pico-newton level forces detected by the vision system are then magnified to the master device. The haptic interface is coupled directly to the slave system with constant homothetic factors.

Bandwidth is the first essential factor for haptic feedback [14]. In situations lacking direct infield force sensing, vision becomes a valuable solution. The acquisition frequency of the visual detection should allow high dynamic perception and should match the human perception threshold (1kHz). In micromanipulation sensing techniques, few vision sensors allow high speed force measurement. Quadrant photodiodes achieve more than 1 MHz but it is difficult to treat unsymmetrical conditions. Images acquired from fast cameras are difficult to process at high speed rates satisfying the haptic frequency requirement [21]. The approach that has been proposed in our previous work is to use DVS, whose pixels detect scenes' contrast changes rather than absolute grey level values and send their own data as local information independently and asynchronously.

Robustness to environmental noise is another important factor so that the interaction forces can be reliable regardless of the external perturbations (obstacles, defocusing, impurities, shadows...). The estimation of contact forces in conventional frame-based techniques during touching procedure requires complex image segmentation algorithms that can only operate at low processing speeds. The event based algorithm proposed is more robust than existing high speed visual detection methods for microsphere tracking and is able to achieve the same detection quality as a far more complex frame based algorithm that runs one order slower.

These two major difficulties –speed and robustness– have been resolved in our previous work [17]. A fast and reliable haptic optical tweezers system has successfully been integrated and a complex task to touch a three-dimensional spherical target has finally been accomplished.

B. Multi-trap creation

In a second stage, the goal is to enhance further the capability of the system to create force feedback on multiple traps. Different from single-trap systems, the laser actuation mode exerts a significant impact on the quality of the force measurement for multi-trap systems. Laser can be moved actively or passively. The method with which micro/nanostage moves while the laser remains fixed is called "passive" actuation, see Fig.2 (left). In this case, the camera view is fixed with respect to the laser thus the entire sensor resolution can be used to image the closet neighbourhood of the trapped bead. Any slight deviation of the bead from the laser center can be precisely captured as force information. However, by using laser actuators, such as SLM or AOD [22], the laser beam becomes "active". In a conventional optic setup, the laser spot is no longer centred in the camera view, see Fig.2

(right). The trapped object travels a large range following the movement of laser trap. The bead-laser relative distance then becomes difficult to calculate. For each moment, not only the sphere position but also the laser center should be detected in real-time to feedback forces.

Therefore, successful haptic feedback on multi-trap holographic optical tweezers is rare due to the difficulties encountered in detecting continuously the laser center and the low resolution during force measurement. Therefore, a specific optical design that overcomes this problem should be found. Our approach is to carefully place the galvanometer scanning mirror system and the vision sensor in the optical path.

The galvanometer scanning mirror system (GVS002, Thorlabs) is used for time-multiplexing multiple optical trapping in our setup, see Fig.3(b). The galvanometer is an optically bilateral system, where the white light goes through in exactly the opposite direction to the laser beam. The positioning of the galvanometer is crucial as has been explained previously. The asynchronous vision sensor DVS should be placed at the laser generator side with respect to the galvanometer system to have the laser spot constantly fixed in the scene. However, the white light passes through the galvanometer mirrors first and then enter the asynchronous vision sensor. In this way, the vision sensor can effectively concentrate the detection on the close neighbourhood of the different trapped beads to achieve the optimal use of the sensor resolution. The simultaneous force measurement for multi-trap is obtained by time-multiplexing the event based vision sensor as the same principle of the multi-trap generation.

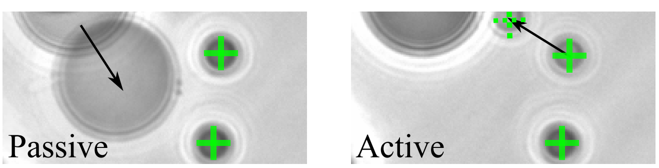

Fig. 2. Laser actuation: (left) Passive mode where the laser is fixed while the microstage moves; (right) Active mode where the laser moves. The green crosses represent the two laser trap centers.

C. Experimental setup

The second version of the experimental setup is shown in Fig3(c) which contains: the same laser source, the high numerical aperture objective and the micro/nanostage. The haptic device used is Omega.3 (Force dimension). The galvanometer is placed in the optimal position for better force measurement. The scaling gains for the haptic coupling are: 1.6×10^{-4} for the position and 5.6×10^{-12} for the force. No further coupling control has been necessary to obtain a stable and useful system. The optical trap stiffness has been calibrated on the microprobe with $2.3 \times 10^{-6} N/m$ using the power spectrum method. All the system control, visual processing and data recordings use a single desktop PC with an Intel Xeon duo-core CPU running at 2.93GHz. Fig3(d) shows a photo of the whole optical system.

D. Visual detection system

Conventional image processing technique is not capable of tackling complex visual information in kHz order thus is not suitable for systems running a haptic loop. The asynchronous event-based vision sensor is thus adopted. The idea of event based vision originates from the neuromorphic engineering community and mimics biological retinas. A review of the existing similar sensors is surveyed in [23]. One of such sensors, called Dynamic Vision Sensor (DVS), which possesses a resolution of 128×128 pixels, is used for fulfilling the work in this paper. The DVS's output contains only asynchronous events that signals scene luminance changes in log intensity since the last event emitted. When the luminance change exceeds a threshold, an event of polarity ON or OFF is generated depending on whether the intensity is increased or decreased. Each pixel is independent thus the event stream is asynchronous. The timing of events is conveyed with a temporal resolution of approximately 1 µs. DVS connects to computers using a fast USB link. Fig.3(a) shows an image created by accumulating DVS's events within 30ms.

To track the position of microspheres, a special event based processing algorithm is implemented to estimate the center and the radius of the probe at a speed of 1 kHz. Compared with other high speed micro-particle tracking algorithms, e.g. centroid [15], cross-correlation or symmetric transform [24], our algorithm smartly uses the event data, which is naturally produced along the edges of object, to fit a circular form in a least square sense. It lowers the computational cost and meanwhile achieves better robustness. Furthermore, an additional robust method is used to eliminate outlier events. The status of beads, either trapped or lost, is constantly checked by computing the mean event rate. The event rate approaching zero indicates a lost of bead so the force should be instantaneously turned off for safety.

Light intensity is an important factor for the successful use of DVS. Insufficient light will degrade the DVS's pixel bandwidth. Therefore, a LED of strong intensity (OSRAM,+2.17W) and of hot white color is chosen.

E. Multi-trap synchronization

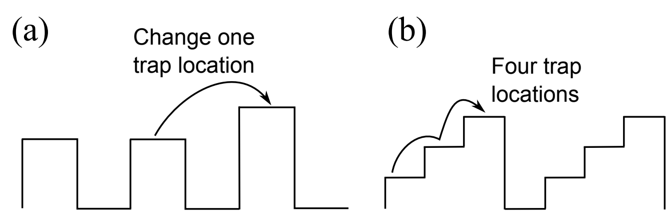

Fig. 4. (a) The analog input signal used to control the angular positions of the galvanometer mirror (X axis). Two traps are generated in this case. (b) Multiple traps more than two can be generated by using step-like wave (X axis).

The galvanometer scanning mirror system is a high speed motor controlled mirror system capable of reflecting light to different directions. The position of the laser spot can thus be adjusted on the fly by controlling the mirrors' positions.

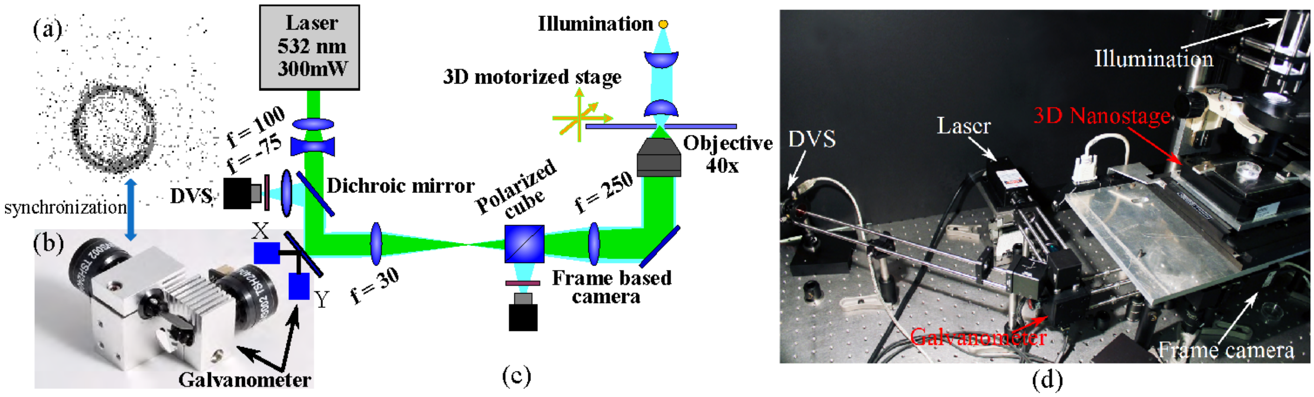

Fig. 3. (a) An image shows the accumulated events within 30ms. (b) The galvanometer scanning mirror system from Thorlabs, whose control signal should be synchronized with the switching signal of DVS views. (c) The optical schema of the multi-trap force feedback optical tweezers. The focal length is in millimeters. (d) A photo of the optical system.

The mirror position control requires analog voltage input thus a data acquisition card (National Instrument PCI6221) is disposed to generate the input signal. Square waves of 250 Hz are used to switch the mirror positions to create two traps, see Fig.4(a). By changing the high and low electrical level of the square wave, one changes the position of the trap correspondingly. If step-like wave is used instead of square wave, multiple traps more than two can be generated, see Fig.4(b). The galvanometer used here includes two separated mirrors to drive light in X and Y directions.

Time multiplexing requires to synchronize the control signal of the galvanometer to the switching signal of DVS view. Synchronization with DVS breaks if the transition of the square wave amplitude is not smooth. When changing trap positions, new square wave interrupts the previous square wave at any moment thus damages the equilibrium of time sharing between two traps. In the current software, the exact moment of wave transition cannot be fully controlled on our non-real-time operating system. This justifies the use of a hard real-time platform in the near future. At the moment, this default has been partially corrected in a special synchronization procedure by the combined use of DVS's synchronization signal and the timestamps of events described as follows.

DVS is equipped with an external synchronization pin that has the ability to inject synthetic signals into the event stream on each falling edge detected on the pin, which itself connects to the wave generation clock. The synchronization signal is thus generated at the exact moment of the trap swap. In the current DVS prototype, a synchronization signal is represented in the form of a status bit attached to the generated event data. Due to software implementation reasons, e.g. the use of socket protocol UDP in data acquisition, the successful recording of each falling edge is not guaranteed. Therefore, the DVS synchronization signal cannot be used alone to establish the correct event-trap correspondence.

The switching frequency known a priori, the timestamps, clocked by a precise hardware counter in DVS, can be the most essential information to separate DVS's views from different traps. In other words, according to the scanning frequency, timestamp of each event is checked, which acts like a software clock running parallel and independently with the external trap switching clock. However, the timestamp clock deviates gradually from the external signals clock in practise. In other words, the prediction of the precise switching moment by timestamp degrades due to the accumulation errors of timestamps in the long term. Hence, our synchronization strategy is the combined use of timestamps and the synchronization signals of DVS. The whole procedure of establishing event-trap correspondence is illustrated in Algorithm 1.

Algorithm 1 Synchronizing DVS views with different laser traps

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for every incoming event, do
    if there is a synchronization signal attached, then
        mark as the beginning of a switching period.
    end if
    if a period is finished according to timestamps, then
        switch the event-trap correspondence.
    end if
end for
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III. Experimental results

A. Observations from vision system

In time-multiplexing force measurement, the establishment of events-trap correspondence is a critical issue. For the sake of the best detection, experiments have been conducted to carefully examine the details in event generation during trap switching. Several major differences from the single trap situation [16] can be observed.

Firstly, the reason why only one type of event polarity will be retained for processing will be shown. Fig.5 (a) and (b) are time-multiplexed DVS views showing two trapped beads. Events are accumulated every 5 ms. The frame image of Fig.5 (c) shows a more extended view of multi-trapping, where two beads are trapped simultaneously close to an obstacle. Fig.5(a) and (b) correspond to the enclosed rectangles

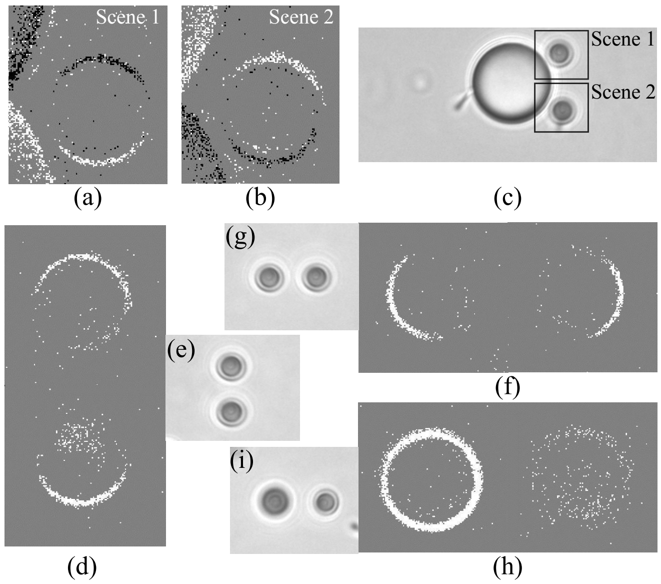

Fig. 5. Images (a)∼(b) shows the DVS views during trap swap. Events accumulation time is 5 ms. ON and OFF polarity dominance occur in a conjugate moment of switching. (c) The enclosed areas in the classical frame image correspond to DVS views (a) and (b). (d)-(i) are three groups of DVS views and their corresponding frame images to show the impact of including scene difference in the event stream.

in Fig.5(c). As illustrated, ON and OFF polarities dominate in a "conjugate" moment of switching. More intuitively speaking, DVS view of scene one may possibly appear events of scene two with the opposite event polarity. Therefore, processing one type of event alone will largely eliminate the problem of undesirable including of the information due to polarity. However, this elimination is not thorough. A small quantity of traces will still be left over. Experiments show that the higher the transition frequency of the galvonometer mirrors, the larger the quantity of undesirable traces be left in another scene. This adds a new type of noise to the current force measurement.

Unlike the situation of a single trap, DVS records now not only the contour of the moving object but also the switching of the entire scene. In short, the DVS events generated by the new setup contain the following information:

- Movements of the beads;
- Scene difference (scene A -scene B) and (scene B -scene A);

in which the second item is undesirable for bead position detection.

To illustrate the types of problems it can cause for position detection, imagine a moment when the Brownian motion is extremely weak, the events will then be generated purely due to scene difference. And if the two beads are located in exactly the same place, there will be no difference between the two scenes thus no event will be generated. Practically, beads do move and have differences. Fig.5(d), (f) and (h) are DVS views of two simultaneous trapped beads with OFF events eliminated. The undesirable generation of events by intensity difference between two scenes persists. Fig.5(e), (g) and (i) are frame images corresponding to the DVS views (d), (f) and (h) respectively. It can be seen that if two spheres are placed either vertically (case (d)(e)) or horizontally (case (f)(g)), the events will be more likely generated on the vertical side or the horizontal side of the contour, respectively. The dominant generation of events is in the same direction as that of the DVS view switching, where scene differences are more likely to appear. To further verify, a test is performed by trapping two spheres of different sizes, see (h) and (i). It can be observed that the events are mostly generated by the big sphere, which completely hides the smaller one during scene transition. As a result, how to strictly separate the movement of objects from the ego movement of the camera (scene background differences here) can be an especially interesting issue in temporal contrast vision sensors as DVS.

B. Experiment on force feedback

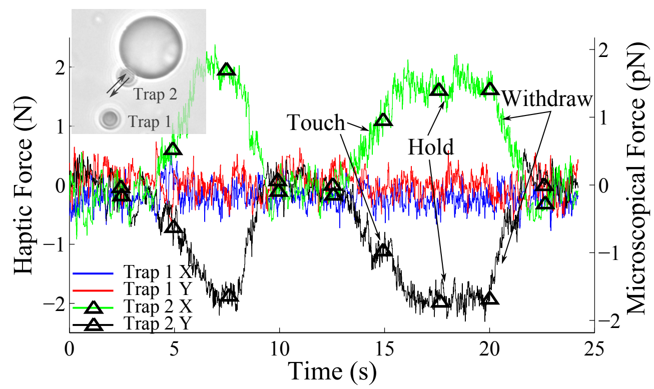

Fig. 6. The forces (XY axes separated) of two beads in two optical traps: one bead is touching a target object, holding and being withdrew from the target, while another bead stays still. The inset image shows a photo of the scene.

Despite of the difficulties mentioned above, our circle fitting algorithm is robust enough to track circles of incomplete contour or contours that are not sharp. Experiments are conducted to show the parallel force-feedback provided by our high speed tracking. Two beads are trapped simultaneously in two optical traps. The probes are polystyrene microspheres of 3 µm, which are treated with a surfactant (Tween-20) to prevent adhesion during contact. Since only one haptic device is available at the moment, it is used to "actively" control the position of one of the microsphere and we leave another one stand still (still exhibits Brownian motion!). Simultaneous control of both traps is possible simply by changing to a more adaptable haptic device. The experimental scene is shown in Fig.6 inset. The bead in Trap 1 stands still and the bead in Trap 2 comes into contact with a big sphere of diameter 10 µm several times. The forces on both traps are measured.

The generated forces are illustrated in Fig.6. It can be observed that the bead in Trap 1 is purely under Brownian motion. The second bead comes to touch the object, be held on for a moment and then be withdrew from the target. This procedure is repeated twice on the curves. This experiment clearly demonstrates that high speed force feedback on multi-trap optical tweezers is plausible, although numerous aspects can still be improved, such as the efficiency of the optical setup, the precision of the synchronization and the robustness lying on the events processing.

IV. Conclusions and perspectives

Optically trapped microspheres can be used as a "probe" to explore the environment in biological and physical researches by measuring the optical forces. We have coupled the haptic device to the multi-trap optical tweezers and have proposed a high speed method for force estimation based on an unconventional event based vision sensor and the associated algorithm. The ideal haptic feedback sampling frequency of 1 kHz is successfully achieved. Multi trapping is successfully created by a galvanometer using a time multiplexing method. DVS data is synchronized with the switching of the mirrors of the galvanometer in order to achieve simultaneous multiple-sphere position detection. The speed and the dexterity of the operator have been greatly improved thanks to the high bandwidth and high fidelity of the force feedback. This technology has strong potential to fulfil the gap of the current market vacancy.

It will be interesting in future researches to expand the force feedback to the third dimension. The high degrees of freedom multi-trap optical tweezers system with highly transparent force feedback may be beneficial in two different scenarios in the future. The first scenario is the ultra-flexible "microhand". Simultaneously controlled beads act as fingers of a human hand in the microworld. They can then be used to hold and manipulate complex biomedical samples. The second scenario is the "microtool end-effector adaptor". In this scenario, the trapped beads are not meant to manipulate other object directly but are used to hold mechanical microtools of more complex structures. The micro-tools are the real end-effectors but they usually do not include force sensors. The optical tweezers thus play the role of both the end-effector actuator and the infield force sensor. The forces exerted on the complex structured tool will be distributed on each attached bead. Therefore the force exerted on the micro-tool can be calculated by combining the forces on the trapped beads. Different shapes of micro-tool end-effectors can be attached to different configurations of traps. This will surely open a brand new way for microscopic force sensing.

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