2D high speed force feedback teleoperation of optical tweezers

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***Abstract*— The optical trap is a powerful non-contact approach for manipulating micron sized objects. Teleoperation of optical tweezers can be performed by coupling with a haptic interface, which allows an efficient robotic device to control positions and get force feedback. This provides users direct and intuitive microscopic interactions. The major difficulty in order for haptic devices to generate a reliable tactile sensation lies in its high frequency requirement of more than 1 kHz. This paper presents a fast force feedback teleoperation system for optical tweezers that attains this high frequency. The used force sensor is a novel event-based camera that transmits output as a continuous stream of asynchronous temporal events thus enabling high speed event-based visual processing. This new sensor is compared to a conventional frame based one to show advantages of our setup. A complex task of exploiting three dimensional target surface is performed demonstrating the robustness and efficiency of the presented method. This is the first time microspheres are used to touch targets of arbitrary form and color, which may interest broad-reaching biological and physical applications.**

I. INTRODUCTION

Optical tweezers are a revolutionary tool for micromanipulation and microscale force measurement [1][2]. Micron-sized objects can be trapped under a focused laser beam under a high numerical aperture microscope. This non-contact technique has been widely used in physics, cell engineering and other fields of micromanipulation. Since the laser may cause damage, silicon or polystyrene micro-beads are used as a "handle" to indirectly manipulate the desired target, such as cells [3]. The trapped bead can also be used as a force "probe" to study biological or physical phenomena at micro-scales [4][5].

Force feedback teleoperation allows high efficiency and fast performance on micromanipulation tasks [6]. The advantage of teleoperation lies in that the user feels the interactions with the object being manipulated. Therefore reliable force feedback assists non-experienced users in performing high failure rate tasks that usually require a huge expertise [7]. The first bilateral coupling of teleoperation system to optical tweezers is reported in [8]. However, the force feedback frequency is too low to provide operators with a reliable sensation. In this paper, we propose for the first time a high speed vision solution dedicated to force feedback on optical tweezers. The trapped sphere serving as a "probe", the user can potentially examine the physical characteristics of the target object, e.g. cells, by touching, thus enabling a broad variety of potential applications, especially in biology. In the following text, "probe" is used to refer to the microsphere trapped by optical tweezers. The force is then estimated by detecting the probe position with respect to the center of the optical tweezers. More profound mathematical analysis on the force can be found in [2].

Bandwidth is the first essential factor for haptic feedback [9]. 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) [10]. Double-trap [11] or multi-trap [12] parallel systems are developed, however the bandwidth problem of such haptic feedback remains unresolved. In micromanipulation sensing techniques, few vision sensors allow high speed force measurement. Quadrant photodiodes achieve more than 1 MHz but remain a four pixel only technique. Images acquired from fast cameras are difficult to process at high speed rates satisfying the haptic frequency requirement [13]. We propose a brand new approach by introducing a high bandwidth asynchronous event-based silicon retina. Its pixels detect scenes' contrast changes rather than absolute grey level values and send their own data as local information independently and asynchronously [14]. The dedicated algorithms are thus frame free and can be operated at high speeds at the order of several kilohertz [15][16].

Robustness to environmental noise is another important factor in order for the interaction forces 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. In [4], an exploration task is performed for the guidance of a probe along a dark flat wall or a corner, which requires only simple image processing techniques. In this paper, we introduce a new setup based on an asynchronous event based vision sensor aiming for the exploration of objects with various shapes and colors. The task that we have accomplished is much more difficult as the probe is used to touch a three-dimensional spherical target. High sampling frequency being an essential element for a realistic tactile sensation, the presented method is more robust than existing high speed vision detection methods in micromanipulation and is able to achieve the same detection quality as a far more complex frame based algorithm that runs one order slower.

The paper is organized as follows: The system design and the experimental set up is presented in Section II. The

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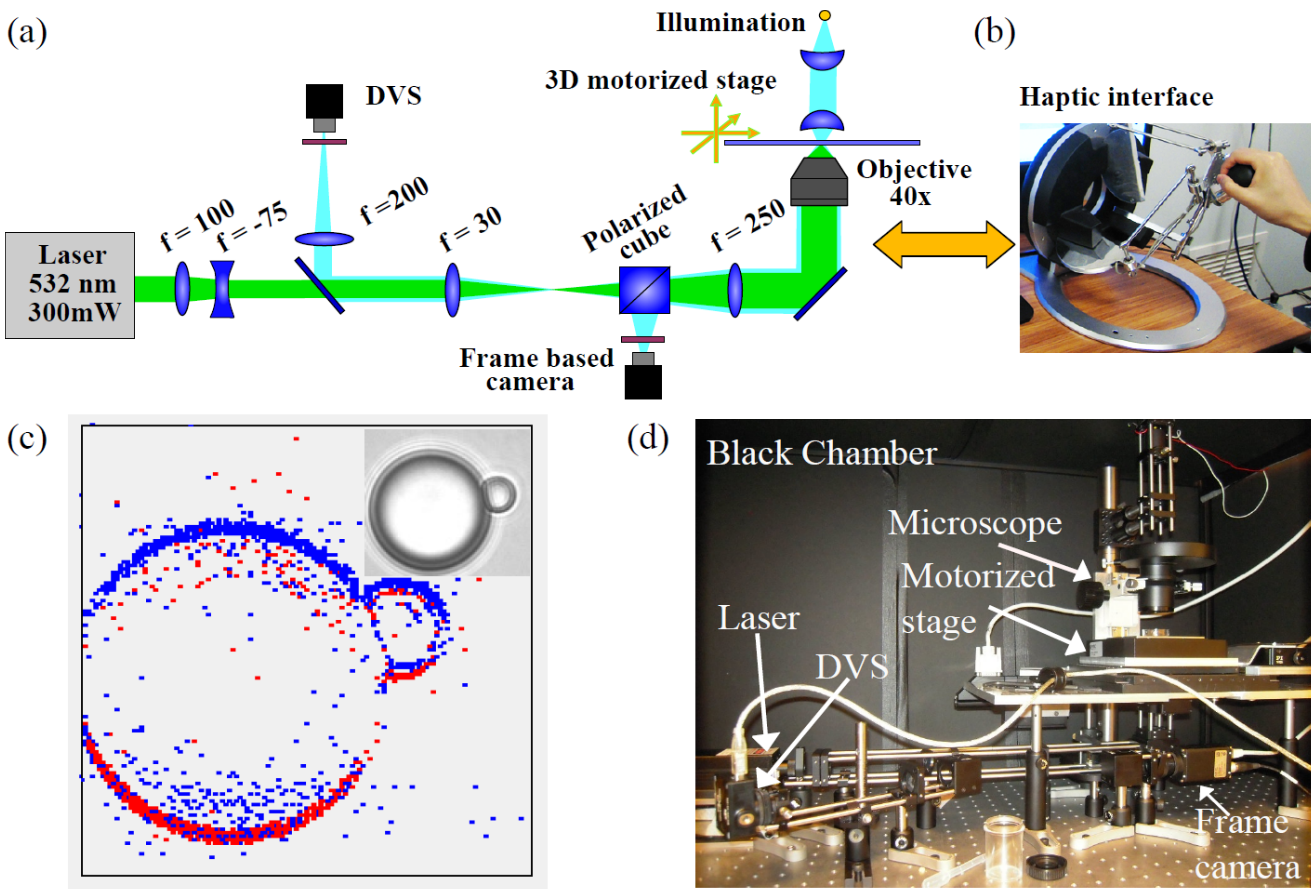

Fig. 1. **(a) A schematic representation of the optical system. (b) Haptic interface - the master device for teleoperation. (c) An accumulation map of events generated by DVS. Red and blue dots represent events of different polarities; The inset shows the correspondent scene in a frame based image. (d) A photo of the whole slave part of the teleoperation system of optical tweezers.**

proposed approach is validated by the three dimensional exploration task presented in Section III. Finally, Section IV concludes the paper.

II. System Description

A. Teleoperation system for optical tweezers

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 single 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. The stiffness is calibrated through the power spectrum of a single particle's Brownian motion under optical tweezers [2]. On polystyrene microspheres of 3µm diameter, the trap stiffness is $1.8\times10^{-5}N.m^{-1}$ for the x-axis and $1.5\times10^{-5}N.m^{-1}$ for the y-axis (room temperature = 18°C).

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 3D motorized stage to generate displacements. The pico-newton level forces detected by the vision system are then magnified to the master device to be sensed by the user. The haptic interface is coupled directly to the motorized stage with constant homothetic factors. The positions of the haptic device are multiplied by a factor of 4×10^{-4} to control the microstage and the measured force is magnified by a factor of 2.0×10^{11} to allow the force to be displayed to the operator (see Table I for parameters summary). Photos of the master system and the slave system are shown in Fig.1 (b) and (d), respectively.

B. Visual detection system

Two types of cameras are mounted in our setup. The first one is a conventional CMOS camera (Basler 659×494 pixels) which allows visual perception for operators.

The second one is the asynchronous event-based vision sensor, called Dynamic Vision Sensor (DVS) [17]. This sensor has a resolution of 128×128 pixels. It originates from the neuromorphic engineering community and mimics biological retinas. A review of the existing similar sensors is surveyed in [18]. The DVS's output contains only asynchronous *events* that signals scene luminance changes in log intensity with respect to the last event emitted [14]. Each pixel is independent. When the luminance change exceeds a threshold, which can be adjusted by software, an event of polarity +1 or -1 is generated depending on whether the intensity is increased or decreased. DVS is not clocked as conventional cameras are. The timing of events is conveyed with a temporal resolution of approximately 1 µs. The absence of events when no change of contrast is detected implies that the redundant visual information usually recorded in frames is not carried in the stream of events. The retina connects to computers using a fast USB link.

Fig.1 (c) compares an event accumulation map (events accumulated during a certain period and then projected onto a 2D plane regardless of their timings) of a bead probe touching a large sphere to the same scene captured by the frame based camera. Dots of different colors represent events of different polarities.

The implemented event processing algorithm is derived from the Hough circle transform [19] to detect spherical objects. The major advantage of Hough transform is that circles can be tracked robustly even in the presence of occlusions or clutters. Event based continuous Hough transform is a newly developed algorithm dedicated to event based sensors, which has been used for Brownian motion analysis [15]. Compared with other high speed micro-particle tracking algorithms, e.g. centroid or cross-correlation, event-based Hough is able to lower the computational cost by updating the sphere positions for every incoming event and meanwhile achieve better robustness. In continuous Hough transform, events generated during the most recent period of time are stored and contributed to the detection by voting circles in Hough space. Older events are eliminated from calculation. This recent period is termed as *"decay period"* hereafter. In a second stage, a centroid is applied on a radial range of 3 pixels in Hough space to achieve a sub-pixel resolution. This algorithm runs at very high speed and is adapted to track spherical beads under optical trap.

Illumination conditions and the event generation threshold should be carefully configured in order to achieve the optimal bandwidth and the needed event rate. During the optical tweezers' stiffness calibration, the event rate lies around 30k events per second (ev/s). In the scenario where the probe touches another object, the typical mean event rate is 50k ev/s. Statistically, a proportion of 30% of total events belongs to the movement of the probe and is used to update the circle position.

To compare with the DVS detection results, images are recorded from the frame based camera during manipulation. Hough transform is available as a built-in function in openCV computer vision library and is directly applied for performance comparison. In what follows the DVS processing is performed in real-time while images are processed off-line solely for comparison use.

All system control, visual processing and data recordings use a single desktop PC with an Intel Xeon duo-core CPU running at 2.93GHz.

Trap stiffness	X-axis	$1.8 \times 10^{-5} N.m^{-1}$
	Y-axis	$1.5 \times 10^{-5} N.m^{-1}$
Scaling gains	Position	4×10^{-4}
	Force	2.0×10^{11}
Frame based sensor	Frame rate	30 fps
Event based sensor	Time stamp	1 µs
Haptic loop	Sampling rate	1 kHz

TABLE I

SUMMARY OF IMPORTANT PARAMETERS

III. EXPERIMENTS AND RESULTS

A. *Task description*

In the search of instrumentation for cell characterization or organelle exploration, biologists require flexible and non-destructive tools to sense the microscopic interaction forces. An important task that has not yet been done with the optical tweezers is to trap a bead to touch an arbitrary target and then feedback the forces. The proposed experiment adapts to this emerging necessity, where a three-dimensional microworld exploration is conducted. The probe used is a 3µm diameter polystyrene microsphere trapped by the optical tweezers. A big microsphere of diameter 10 µm is chosen as the target object, which can be viewed as a cell, a typical element in biological research.

The whole experiments will be conducted in two parts for two types of applications. The first one is the "come-into-contact". The probe is initially in a free state and then it starts to come into contact with a target object. It initiates the basic utility that the probe can be used to sense the stiffness of an object.

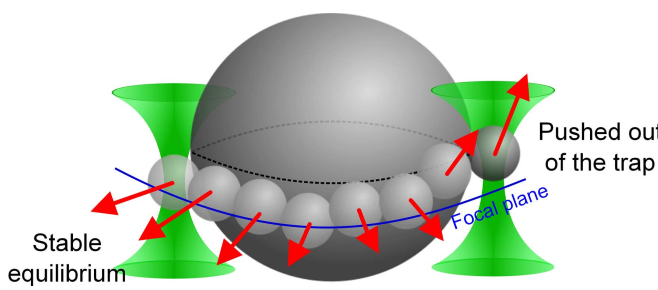

Fig. 2. **A small microsphere (the probe) is moving along the surface of a big microsphere. Initially in an equilibrium position, the probe moves from below the medium height of the surface upward. The combinational force finally drives the probe out of the optical trap due to weak trap stiffness in z axis.**

The second step is to lead the probe to "walk around" a target surface. It allows applications such as scanning the surface topology of a biological element. In our experiment, we choose to use the probe to walk around the surface of a 10 µm microsphere for a first demonstration of proof-of-concept. There are two main reasons for selecting this task. Firstly, the exploration of a non-planar surface of a big microsphere is extremely difficult without force feedback. User feels hard to maintain a constant contact with the circular surface thus the probe trajectory deviates easily. The trapped object escapes due to unstable equilibrium positions as shown in Fig.2. The combinational force may push the probe out of the optical trap due to weak trap stiffness on z axis when contact happens above the medium height of the bead. Reliable force feedback can thus assist users to efficiently tune the interactions on the probe, to conduct it to walk around the shape and to prevent from losing the trap. The second difficulty is from the point of view of vision. The color of the target object is the same as the "probe", which adds more complexities to visual processing than other state-of-the-art work.

B. A comparison with the frame based method

Event based and frame based vision are completely different visual processing frameworks. Due to its redundancy elimination mechanism, event based sensor and algorithms are able to achieve the same processing quality with respect to the frame based correspondences while providing higher detection bandwidth and consuming less computational load. In order to allow comparisons, the power spectrum of the Brownian motion of the probe trapped by optical tweezers will be compared using both vision sensors.

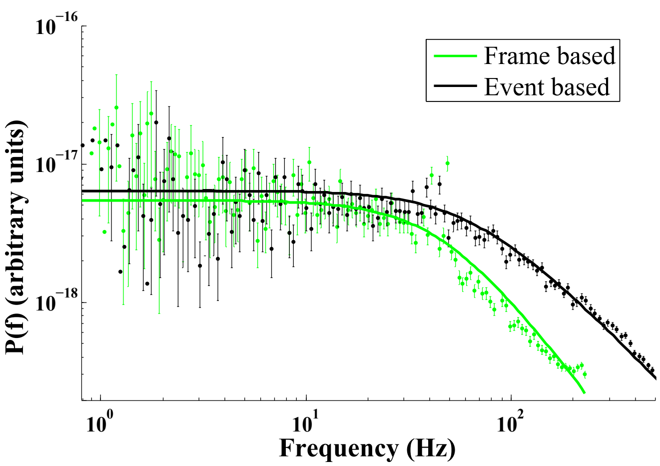

Fig. 3. **A comparison of the power spectra of Brownian motion of the probe detected by both the frame based camera at 460 fps (light color), and the event based vision sensor with equivalent frame rate 1k fps (dark color). The dots are raw data value with the bars their standard deviations. The solid curves are the fitted power spectra.**

Fig.3 compares the results of the power spectra of the Brownian motion of the probe using both cameras. Fig.3 (light color) shows the spectrum using the frame camera running at 460 fps. A region of interest of 70×70 pixels is selected and the exposure time is manually diminished in order to achieve this high frame rate. The cut-off frequency is determined to be 60 Hz.

Fig.3 (dark color) shows the spectrum using DVS with the event based Hough of 1 ms decay period, thus corresponding to 1 kHz equivalent frame rate. The bandwidth of the tweezers is estimated to be 80 Hz, slightly higher than that estimated by the frame based camera. This is because the frame rate of the conventional camera is not *far beyond* the cut off frequency of the optical tweezers, therefore high frequency signals are attenuated.

Special care should be paid in calculating the power spectrum using DVS raw data. Due to DVS's asynchronous unfixed interval timing and the Fourier transform implying a fixed interval sampling, the result will be erroneous if the raw data is used directly. According to DVS's timestamp, the asynchronous small interval data, e.g. 30kev/s can be subsampled to form a regular sequence with a larger interval, e.g. 1 kHz.

As has been shown, DVS is able to achieve a high detection bandwidth as a conventional high speed camera. The event based redundancy-free processing framework is the real benefit brought by DVS that allows high speed force feedback, which will be presented in the section below.

C. First experiment on surface exploration

A first experiment is conducted to demonstrate the possibility of using the trapped bead as a probe to touch and feel the forces during object contact. Fig.4 (a) side view schema illustrates the detail of this procedure. The user displaces the optical tweezers to drive the probe towards the target. Upon contact, the position of the laser spot is closer to the target than the center of the probe. This deviated distance can then be applied to calculate the contact force. In our work, a simple spring model is employed under the assumption that the optical tweezers remain in the linear region. Other complex force models taken into account more factors can also be envisioned. Since the probe is slightly below the medium height of the big sphere, the combinational force will drive the probe descend downwards thus the probe appears defocused, see inset (ii) of Fig.4 (a) . Probe positions (i) and (ii) in the side view of Fig.4 (a) correspond to the top view inset photo (i) and (ii). The force feedback is two dimensional at the moment, which equals to the real force projected onto the focal plane.

Fig.5 illustrates the microscopical and the haptic forces detected by the vision sensor during the first part of the experiment. As expected, the force values start from around

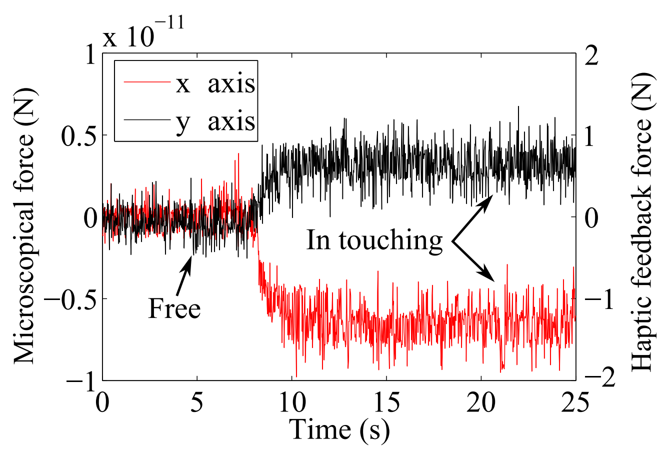

Fig. 5. **Microscopical and haptic Forces measured by the probe during the "come-into-contact" experiment. The microscopical forces along the xy-axes of the probe have standard deviations of 0.83, 0.86** pN **in free state and 1.17, 1.13** pN **during contact.**

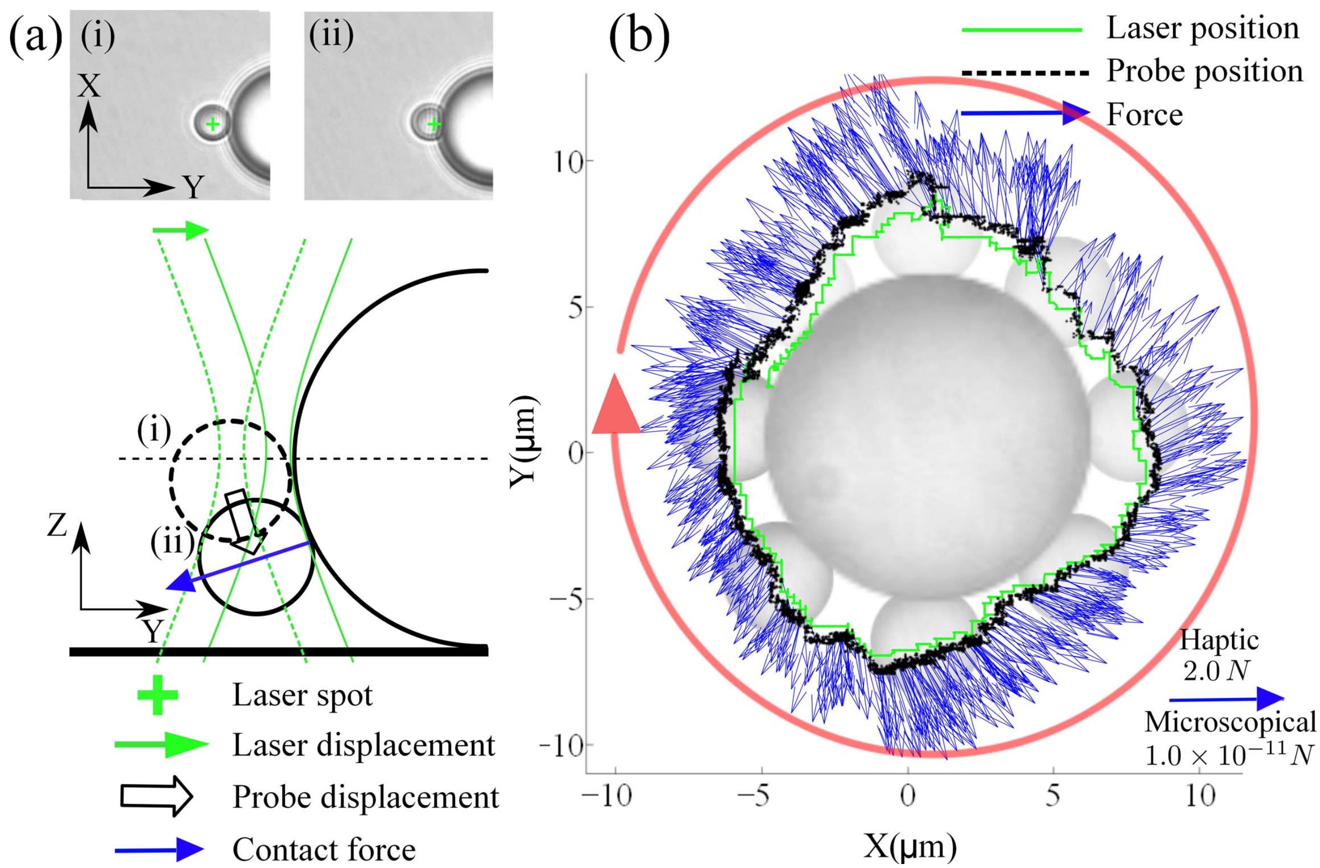

Fig. 4. **(a) shows the probe "coming into contact" with the target object. Inset(i) and inset (ii) show the moment before and while touching, respectively. Below is a side view schematic representation of the "come-into-contact" procedure. The probe locations (i) and (ii) correspond to the inset images (i) and (ii). (b) shows the positions and forces when the probe "walks around" the surface of the big sphere. The probe trajectory is depicted in black dots, the laser position in green line and forces in blue arrows. For clarity, the force arrows are subsampled to one thirty.**

zero in free state and then change to other constant values when in contact. The microscopical forces along the xy-axes of the probe have standard deviations of 0.83, 0.86 pN in free state and 1.17, 1.13 pN during contact. Larger deviations appear when the probe keeps in touching. This implies a few instabilities of the visual detection facing obstacles. During contact, a small proportion of the votes in Hough space may be contributed by events generated from the contour of the target other than that of the probe, thus the detection precision is transiently reduced. This phenomenon is more obvious when the decay period is tuned to be smaller. Longer decay periods can eliminate the artificial vibrations but will reduce the total bandwidth. We choose 1 ms decay period as a compromise.

The second part of the experiment is to "walk around" a "cell". Fig.4 (b) shows the probe trajectory and the contact forces during surface exploration. The green solid curve is the laser spot trajectory and the black dots are the estimated probe positions, which both appear as a circular shape. During the task, force feedback assists the user in maintaining the probe consistently on the surface of the target. As shown in Fig.4 (b), the force directions (blue arrows) remain the same as the radial directions of the large microsphere, which is an expected result. As demonstrated, the difficulty of the task is that the directions of the contact forces are continuously changing during manipulation. The forces are at the order of ten pico-Newton and are sent back to the user at the sampling rate of 1 kHz.

Without force feedback, it is difficult for user to maintain a constant contact on the target surface. The sphere may escape easily or get stuck to the surface if the user pushes the probe too hard. By using the defocusing hint shown in Fig.4 (a) inset (ii), experienced users may still perform this task. However, the concentration on the focusing status is laborious and tedious, thus impractical for long time manipulation. By enabling force feedback, users fulfil the presented task less laboriously, faster and more repetitively than without force. The probe escaping or surface sticking are also far less frequent.

D. Frame based or event based – a qualitative comparison

Among the frame based particle tracking algorithms, the centroid is the most frequently used due to its simplicity. However, it is impossible to apply alone in probe-target contact scenario because large bias will be produced when the calculation region contains obstacles. Moreover, the similarity of light intensity of the probe and the target will further degrade the detection quality if non-robust image processing algorithms are used.

Frame based circle detection algorithms immune to obstacles exist. OpenCV's implementation of Hough transform provides real time performance under the criteria of conventional computer vision in the order of tens of frames per second. It hence has never been successfully applied for high speed micro-particle tracking. Moreover, luminance and focus play an extremely important role in edge detection, which is the prerequisite of the frame based Hough transform. Slight differences in optical configurations may produce large detection uncertainty.

The key advantage of using event based vision is that traditionally complex algorithms can be applied all satisfying the high speed processing requirement. By employing the event based method, the effective position refreshing rate of the probe attains 15 ± 5kHz during the "walk around" experiment while all the system controls and haptic coupling are running. The processing speed is much higher than the desired haptic feedback frequency of 1 kHz. Last but not least, DVS serves as a robust hardware edge detector. By employing the edge information directly, the presented method has been applied successfully to track a probe in contact with an object of arbitrary form and color, which shows the advantage of our method facing obstacles and environmental noise.

IV. Conclusion and perspectives

Haptic force feedback assists operators in manipulating objects, keeping a reasonable contact force, blocking for dangerous manipulation, etc. The optically trapped microsphere 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 optical tweezers and have proposed a high speed method for force estimation based on an unconventional event based vision sensor and algorithm. The presented system demonstrates the possibility of high bandwidth reliable pico-newton level force sensation and initiates a broad range of microscopical applications. DVS's frame-free and redundancy elimination mechanism allows the dedicated algorithm to run at an unprecedented speed in the order of tens of kilohertz. The ideal haptic feedback sampling frequency of 1 kHz is successfully achieved. A complex task of manipulating the probe for non-planar surface exploration has been demonstrated for the first time. It shows better robustness of our algorithm than the existing methods for high speed particle tracking.

Further researches aim to reduce the vibration of the current system when the probe is in fixed contact with the target. It will also be interesting to expand the force feedback to the third dimension. Employing a high speed actuation may further enhance the global performance. Finally, the DVS sensor can be integrated into systems in which multiple optical traps are coupled with parallel haptic devices.

V. Acknowledgement

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References

[1] D. Grier, "A revolution in optical manipulation," *Nature*, vol. 424, no. 6950, pp. 810–816, 2003.

[2] K. C. Neuman and S. M. Block, "Optical trapping," *Review of Scientific Instruments*, vol. 75, no. 9, pp. 2787–2809, 2004.

[3] A. Ashkin, J. Dziedzic, and T. Yamane, "Optical trapping and manipulation of single cells using infrared laser beams," *Nature*, vol. 330, no. 6150, pp. 769–771, 1987.

[4] C. Pacoret, R. Bowman, G. Gibson, S. Haliyo, D. Carberry, A. Bergander, S. Régnier, and M. Padgett, "Touching the microworld with force-feedback optical tweezers," *Optics Express*, vol. 17, no. 12, pp. 10 259–10 264, 2009.

[5] D. Haliyo, S. Régnier, and J. Guinot, "[mü] mad, the adhesion based dynamic micro-manipulator," *European Journal of Mechanics-A/Solids*, vol. 22, no. 6, pp. 903–916, 2003.

[6] A. Bolopion, H. Xie, S. Haliyo, and S. Régnier, "Haptic teleoperation for 3D microassembly of spherical objects," *IEEE/ASME Transaction on Mechatronics*, vol. 17, no. 1, pp. 116–127, 2012.

[7] H. Xie and S. Régnier, "Development of a flexible robotic system for multiscale applications of micro/nanoscale manipulation and assembly," *IEEE/ASME Transactions on Mechatronics*, vol. 16, no. 2, pp. 266–276, 2011.

[8] F. Arai, M. Ogawa, and T. Fukuda, "Indirect manipulation and bilateral control of the microbe by the laser manipulated microtools," in *IEEE International Conference on Intelligent Robots and Systems*, 2000, pp. 665–670.

[9] A. Bolopion, B. Cagneau, S. D. Haliyo, and S. Régnier, "Analysis of stability and transparency for nanoscale force feedback in bilateral coupling," *Journal of Micro - Nano Mechatronics*, vol. 4, no. 4, pp. 145–158, 2008.

[10] J. Colgate and G. Schenkel, "Passivity of a class of sampled-data systems: Application to haptic interfaces," *Journal of Robotic Systems*, vol. 14, no. 1, pp. 37 – 47, 1997.

[11] K. Onda and F. Arai, "Multi-beam bilateral teleoperation of holographic optical tweezers," *Optics Express*, vol. 20, pp. 3633–3641, 2012.

[12] Ditto, "Parallel teleoperation of holographic optical tweezers using multi-touch user interface," in *2012 IEEE International Conference on Robotics and Automation (ICRA)*, may 2012, pp. 1069 –1074.

[13] R. Bowman, C. Pacoret, S. Haliyo, S. Régnier, G. Gibson, and M. Padgett, "High-speed camera particle tracking and force measurement, with real-time haptic feedback," in *OTA Conference*, 2009.

[14] P. Lichtsteiner, C. Posch, and T. , Delbruck, "A 128×128 120db 15μs latency asynchronous temporal contrast vision sensor," *IEEE Journal of Solid-State Circuits*, vol. 43, no. 2, pp. 566–576, 2008.

[15] Z. Ni, C. Pacoret, R. Benosman, S. Ieng, and S. Régnier, "Asynchronous event based high speed vision for micro-particles tracking," *Journal of microscopy*, vol. 245, p. 236244, 2012.

[16] Z. Ni, A. Bolopion, J. Agnus, R. Benosman, and S. Régnier, "Asynchronous event-based visual shape tracking for stable haptic feedback in microrobotics," *IEEE Transactions on Robotics*, vol. 28, no. 5, pp. 1081 – 1089, 2012.

[17] "http://siliconretina.ini.uzh.ch/wiki/index.php."

[18] T. Delbruck, B. Linares-Barranco, E. Culurciello, and C. Posch, "Activity-driven, event-based vision sensors," in *IEEE International Symposium on Circuits and Systems*, 2010, pp. 2426 –2429.

[19] P. V. C. Hough, "Machine analysis of bubble chamber pictures," in *Proc. Int. Conf. High Energy Accelerators and Instrumentation*, 1959, pp. 554–556.