Invited Article: A review of haptic optical tweezers for an interactive microworld exploration

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This paper is the first review of haptic optical tweezers, a new technique which associates force feedback teleoperation with optical tweezers. This technique allows users to explore the microworld by sensing and exerting picoNewton-scale forces with trapped microspheres. Haptic optical tweezers also allow improved dexterity of micromanipulation and micro-assembly. One of the challenges of this technique is to sense and magnify picoNewton-scale forces by a factor of 10^{12} to enable human operators to perceive interactions that they have never experienced before, such as adhesion phenomena, extremely low inertia, and high frequency dynamics of extremely small objects. The design of optical tweezers for high quality haptic feedback is challenging, given the requirements for very high sensitivity and dynamic stability. The concept, design process, and specification of optical tweezers reviewed here are focused on those intended for haptic teleoperation. In this paper, two new specific designs as well as the current state-of-the-art are presented. Moreover, the remaining important issues are identified for further developments. The initial results obtained are promising and demonstrate that optical tweezers have a significant potential for haptic exploration of the microworld. Haptic optical tweezers will become an invaluable tool for force feedback micromanipulation of biological samples and nano- and micro-assembly parts. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4818912]

I. INTRODUCTION

Micro- and nano-technologies are, in theory, very attractive. Theoretical models predict incredible properties for nano- and micro-structures. But in practice however, researchers and inventors face an unknown puzzle: there is no analogy in the macroworld that can prepare operators for the unpredictability and delicacy of the microscopic world. Existing knowledge and know-how are experimentally insufficient. Exploration is the most delicate and unavoidable task for micromanipulation, microfabrication, and microassembly processes. In biology, the manipulation and the exploration of single cells or protein properties is a critical challenge.\textsuperscript{1,2} This can only be performed by an experienced user. These procedures are highly time-consuming and uneconomical.

Well-designed user interfaces and force feedback teleoperation increase the achievable complexity of operations and decrease their duration,\textsuperscript{3} because the system replicate the lost mechanical interaction between the operator hands and the targeted object. However, in the microworld, several works have considered the coupling of existing micromanipulators to commercial or prototype haptic devices with little successes.\textsuperscript{4-6} Indeed, the feedback is dependant on the degrees of freedom of the platform, the range of scaling and the type of interaction to render. Compared to other techniques, optical tweezers\textsuperscript{2} seem to be more promising for the integration of the robotic technique of force feedback teleoperation (see Figure 1). Optical tweezers are a very versatile tool and the quality of possible force feedbacks can be improved by the techniques discussed in this paper. This paper highlights a new approach: to rethink the design of micromanipulators in order to reliably and usefully render the interaction through the user interface. Haptic optical tweezers have a high potential. The sensations that we can perceive with the tweezers allows us to picture these nimble microprobes as an extension of our fingertips.

Appropriate techniques to get the user a high quality force feedback with optical tweezers are discussed. Better dexterity is achieved and tasks of higher complexity are performed with little knowledge and implementation of the haptic teleoperation methods. The principles for interactive micromanipulation systems and the advantageous properties of optical tweezers are summarized in Sec. II. The different existing components and techniques of optical trapping are summarized and their drawbacks for haptic purposes are highlighted, in Sec. III. In consequence, new designs specific to haptic applications are discussed in detail in Sec. IV based on the most recent experiments described in the literature. Finally, the prospects brought by this new approach are carefully highlighted in order to encourage further developments in this domain in Sec. V.

II. A DEXTEROUS EXPERIMENTAL PLATFORM

Every day interactions and manipulations are possible because of our remarkable sensors (our eyes and proprioceptors systems) and effectors (our hands and muscles). Traditional tools for visualizing and interacting with the micro world are not nimble or transparent. Microscopes and micromanipulators historically do not lend themselves to intuitive interaction or handling, because vision is two-dimensional, force sensors...
are rare and the degrees of freedom are reduced. Intuitive interactions and control are especially confounded because of the particular phenomena of the microworld.

A. A dexterous micromanipulation technique

Micromanipulation experiments are often poorly repeatable, time-consuming, and costly, because of unique physical phenomena at this scale. Surface interactions become more significant than volume interactions for objects smaller than 500 μm. Particles tend to adhere and become bound to handling tools or substrates, or surface forces interact with low inertia particles to produce huge accelerations which can damage or eject samples.

Many handling techniques have been designed to address the adhesion problem. Current designs are focused on the development of miniaturized microtools with functionalized surfaces (atomic force microscopy (AFM) probes, microgrippers or potential field levitation and non-contact guiding (optical tweezers, electrophoresis, magnetics tweezers, electrohydrodynamics, microfluidics, etc.).

In this paper, we will only consider grasping phenomena that allow manipulation of individual independent microscopic tools (electrophoretic and microfluidics do not permit isolation of a single effector). AFM and microgrippers allow independent displacement and application of high amplitude forces (10–10⁴ pN). However, the effectors are large and therefore adhesion, inertia, and visual obstruction limit their performance. Electromagnetic techniques have a localized magnetic field, but it is difficult to independently manipulate several robots. Also, electromagnetic techniques can only be considered as an independent tool when the properties of the trap probe are very different from the sample nature, such as proteins, cells or non magnetic micro-assembly parts. Optical tweezers (OT) avoid many of the limitations of competing techniques (see Table I for comparisons). Compared to other micromanipulation techniques, OT offer greater versatility. Optical trapping relies on an immaterial electromagnetic field produced by highly focused laser light. This produces optical forces (<100 pN) which are effective for the manipulation of particles between 100 μm and atomic scale. A highly focused laser produces a localized three-dimensional electromagnetic field that stably traps spherical dielectric microtools. This probe is then easily actuated by deflecting or the defocusing the laser. The optical forces are easily modelled and three-dimensional trap stiffness can be estimated experimentally. Particle tracking allows the force on the probe to be measured (see Sec. III C).

There are many experimental setups that use high speed actuation (1 GHz bandwidth) and high precision force measurement (femtoNewton). Time or spatial sharing of the laser power also offers parallelisms possibility of trapping: experiments have shown that more than 200 parallel traps or till 9 parallel sensors have been accomplished on a single system. These properties of optical tweezers, i.e. high speed, high precision, and the capability for multiple independent interactive probes, allow unprecedented opportunities for teleoperative control of microscopic systems. The techniques for efficient construction of the force feedback interfaces are detailed in Sec II B.

B. A dexterous user interaction for micromanipulation

Force feedback teleoperation techniques originate from nuclear energy plants, where maintenance tasks can only be performed from a distance. The aim of these techniques is to recreate the bilateral interaction between the user and an unreachable environment; in others words, touch sensations can be recovered on a system where the mechanical linkage is disconnected. In our case, microscopic particles are mechanically disconnected from the user’s hands. Teleoperation techniques can be extended to micromanipulation platforms in the following way. A master robot, also called the active joystick or the haptic user interface, is connected to a slave robot in our case the OT platform:

- The position orders are recorded by the interface handle, scaled and used to command the microtool displacements.
- At the same time, the scaled forces which are measured in the microworld are fed back to the user through the motors of the active joystick.

This is a bilateral process named the “haptic coupling loop” (see Figures 2(b) and 2(d)). The characteristics of this kind of automatic scheme are well known. Stability and transparency are the main issues for an accurate bilateral
transmission. Stable systems do not diverge from equilibrium positions. For bilateral coupling, this state can be evaluated by the sufficient condition of passivity: the ability of a system to not add energy in the loop. The transparency can be defined as the degrees of reliability and latency of the transmission, measured by the frequency bandwidth of the system. It is important to note that human temporal frequency bandwidth is estimated up to 1 kHz for force perception and over 10 kHz for textures. This means that human hands are able to perceive discontinuity of the signal under this sampling limit. It is critical that the bandwidth and sampling of all components and coupling of the system are over those thresholds.

The most realistic force feedback is obtained with a scheme called direct coupling, because it is only composed of fixed homothetic scaling gains (see Figure 2(d)). Unlike passive coupling (see Figure 2(b)), direct coupling does not possess a filter to reduce information reliability and response time. It therefore has great fidelity, and is referred to as a transparent coupling. However, it is not unconditionally stable, and the stability must be carefully controlled for safe use.

Direct coupling is even worse in the case of micromanipulation, because high scaling effects appear: position information is scaled from milli- to micrometers, and forces are scaled from imperceptible nanoNewton to the human perception thresholds (0.01 N for fingers, >1 N for the hand). These huge scaling factors amplify the signal noise and measurement uncertainties, reducing system stability and the operator’s understanding. For example, a bilateral system including of an AFM tip (see Figure 2(a)) requires additional damping components in order to maintain stability during transitions from contact to non-contact, due to adhesion (see Figure 2(b)). Since damping factors strongly filter high frequencies, direct feedback of measurement is, in this case, not usable and an artificial enhanced metaphoric feedback must be designed instead. Unlike AFM conditions, the force vs. position curve of OT (see Figures 2(c) and 2(d)) presents two significant advantages: the absence of hysteresis and the absence of discontinuities due to adhesion. Additionally, optical tweezers act as a natural spring damping element which provides sufficient damping to maintain stability. Optical tweezers, operating in aqueous medium, have good stability and transparency properties with direct coupling (no energy dissipation, no filters needed). However, pioneers works focused on other problems and did not emphasize this potential.

C. Pioneering works

Vigorous activity in the optical tweezers community has been devoted to the improvement of user interface: such as
joysticks, \textsuperscript{36} hand tracking, \textsuperscript{37, 38, 108} multitouch table, \textsuperscript{39, 40} haptic interface. \textsuperscript{34, 35, 44–46, 85, 86} Other works have reported connecting a haptic device to optical tweezers without describing results or sensations. \textsuperscript{41–43}

Arai \textit{et al.} \textsuperscript{44} achieved the first haptic coupling for OT in 2000, and also identified different limitations of the sensors used. Actuators and sensors limit either the system bandwidth or the working domain. At that time, the available cameras had slow frame rates (CCD: 15 frames/s) and could not be included in a control loop. As a result, the actuator and sensor used (microscope stage and quadrant photodiode) limited the stability and transparency of this system, resulting in a low feedback amplitude (\(< 1 \text{ N}\)).

Those technical limitations explain choices made by Basdogan \textit{et al.}, in 2007, in order to propose model-based feedback for guidance assistance. \textsuperscript{45, 46} By not having measurement and feedback of real forces, the system is not considered as bilateral and the stability issues are avoided. The virtual force feedback can then be increased on the handle with no consequences. With a 3D piezoelectric scanner and scene recognition techniques, this method allow to avoid obstacles and perform efficient microparticle dockings.

Still, this guidance feedback is limited to simple and controlled scenes, and does not fulfill the need of preliminary explorations with real feedback. To obtain stable bilateral coupling, efforts must be focused on improving the performance of the optical experimental setup. For a useful force feedback teleoperation between a user and the microworld, the important parameters of the new design are:

- Interactive mobility (workspace, degrees of freedom and measurement, parallelism)
- Bandwidth (reactivity, dynamics of the system, fidelity of the information, transparency)
- Feedback intensity (perceptible force amplitude, stability limitations, effective assistance and user safety)

\section*{III. INTERACTIVE OPTICAL TWEEZERS}

Interaction between two objects means the whole process of action-reaction. In teleoperated manipulation, an interactive system possesses actuators, sensors, and a bilateral transmission to interact with the user. This section examines why, in OT platforms, the working domain of sensors is very small, when high speed actuation is used. \textsuperscript{34, 35} It demonstrates the incompatibility of previous experimental workbenches for the sought performances of interaction involving high speed and dexterous working space. The right choice of the actuators and sensors is highly important for force feedback applications and is explained in detail.

\subsection*{A. Displacement techniques}

Displacement in OT systems can be achieved by moving the platform or moving the laser beam, referred to hereafter as stage-based or laser-based actuations. In the stage-based techniques, \textsuperscript{37} the laser beam is fixed and an actuated stage allows motion of the sample. The desired target comes to the laser spot (see Figures 3(a) and 3(b)). This trap is always aligned with the optical axis, which is very convenient for the force measurement. Their heavy mechanical parts state microscope stages as the slowest available actuation techniques. \textsuperscript{48} This configuration is convenient for high quality force measurement like photonic force microscope, \textsuperscript{48} but not for the high speed control of the trap. Teleoperation techniques need high temporal bandwidth, which is why high speed actuation techniques based on deflection must be used.

The deflection technique uses special devices to change the laser direction from the light path. A small angle deviation of a lens or a mirror on the laser path shift the beam trajectory from the optical axis of the experimental setup. The laser is then guided with a telescope to the objective aperture. This deflection angle is used to displace the laser spot on the sample plane (see Figures 3(c) and 3(d)). When the deflection is achieved by a system with low inertia, the actuation is very fast, with response times down to 1 $\mu$s. \textsuperscript{23, 49} Many methods exist for optical deflection \textsuperscript{17, 50} and Figures 4(b)–4(f) presents the optical schemes of the available techniques for high speed positioning. Table II summarizes the performances of different available components (in 2012).

The cheapest of the fast actuators (>1 kHz, see Table II) are the galvanometers, i.e. tiny mechanical motors with high resonance frequency (<10 kHz). These deflectors are used in several OT setups and in particular for
FIG. 4. Different actuators used in optical tweezers. (a) Motorized stage: MS; (b) Piezo-Motorized Lens: PML; (c) Piezo-Motorized mirror: PMM; (d) Galvanometers: G; (e) Acousto-optical deflector: AOD; (f) Spatial light modulator: SLM.

Advanced control schemes. Several experimental setups using piezoelectric mirror scanner promise good results for small deflection angles. Three-dimensional positioning is possible with an additional z-axis piezoelectric scanner which is fixed on a mirror or a lens on the light path. Parallel trapping of multiple objects is possible with a single laser by temporal separation of the laser power.

The quickest actuators are presently the acousto-optical deflectors (AOD) (see Table II for performance details), where acoustic standing waves in a crystal are used as a diffractive grating. This phenomena creates interferences of different orders. As only the most intense beam (1st order) is isolated, power losses are significant (>30%), however speed performances are excellent with more than 1 GHz bandwidth.

A different approach is proposed by holographic techniques. Special liquid crystal devices (LCD), named spatial light modulators (SLM), allow phase modulation of the laser light. The resulting interference patterns create several spatially addressable spots. The usual frame refreshment rate, i.e., sampling rate, is 60 Hz following the typical LCD frequency. However, new SLM techniques achieve better speed performances (>200 Hz). The particularity of those devices is the spatial sharing of the laser power which allows more than 200 independent optical traps and therefore collaborative operations of microtools. SLM are also the most convenient techniques to achieve three-dimensional displacement (see Table II).

Actuation of optical traps by deflection of the laser is efficient and elegant, but has the downside of changing the alignment between the optical axis and the sensors. New strategies for force measurements must be developed to deal with the properties of reflective or interferometric deflection phenomena.

B. Impact of the laser deflection

To our knowledge, advanced experimental setups for simultaneous actuation and measurement only allow steering within a workspace of less than 10 μm. This small working domain is due to laser misalignment induced by the deflection.

At this stage, it is useful to recall the measurement principle of optical tweezers. A tiny focusing of the gaussian laser is achieved by using a high with a high numerical aperture microscope objective. In this configuration, the

| TABLE II. Comparison of usual optical tweezers actuators according to the supplier’s data-sheets. Abbreviations: MS: Motorized stage; PS: Piezoelectric stage; G: Galvanometer; PMM/PML: Mirror or lens mount on a piezoelectric scanner; AOD: Acousto-Optical Deflectors; SLM: Spatial Light Modulator; PI: Physik Instrument; CT: Cambridge Technology; QT: QUANTA TECH. |
|-----------------|----------|----------|----------|----------|----------|----------|
| Model           | Supplier | Dim      | Multi-trap | Beam diameter | Bandwidth (kHz) | Spatial resolution | Maximal range | Optical loss | Price estimation |
| M-126.DG1 (×3)  | PI       | 3D       | No        | 7 mm         | <0.005       | 100 nm           | 25 mm         | 0           | € € € € € € |
| P-563.3CD XYZ   | PI       | 3D       | No        | 25 mm        | <0.015       | 0.5 mm           | 300 μm        | 0           | € € € € € € |
| 6200H           | CT       | 2D       | Temporal  | 7 mm         | <10          | 8 μm/μm          | ±350 mtrs     | <3%         | € € € € € € |
| S325            | PI       | 3D (Z, θx, θy) | Temporal | 25 mm        | 1–2          | 0.1 μm/μm        | ±50 μm, 4 mtrs | <3%         | € € € € € € |
| DTSXY           | QT       | 2D       | Temporal  | 6.7 mm       | <30 000      | 25 μm/μm         | ±26 mtrs      | >40%        | € € € € € € |
| PLUTO           | Holoeye  | 3D       | Spatial   | 8 mm         | 0.060        | 1920 × 1080      | 100 μm        | € € € € € € |

resulting electromagnetic field induces optical forces on objects within the focus. In the microscaled case in particular, these interaction are well-known on the spherical dielectric object: the force can be compared to the action of a linear 3D spring around a central equilibrium position, i.e., the laser focus\(^ {31,61} \) (see Figure 2(c)). The proportional factor between the optical forces, \( F\_{\text{opt}} \), and the relative position of a microsphere, \( X\_{\text{sphere}} - X\_{\text{laser}} \), is then defined as the trap stiffness, \( K \), within the OT linear domain

\[
F\_{\text{opt}} = -K \times (X\_{\text{sphere}} - X\_{\text{laser}}). \tag{1}
\]

Moreover, due to the over-damped dynamics in micro-scale aqueous environment, inertial factors become negligible compared to viscous effects (low Reynolds flow\(^ {62} \)). The force balance can be considered as a static equation

\[
0 \approx F\_{\text{others}} + F\_{\text{opt}}. \tag{2}
\]

The interaction of this microspherical probe, \( F\_{\text{others}} \), with its surrounding can then be estimated from the position measurement. This interesting property provides a simple and reliable indirect method for force measurement.

\[
F\_{\text{others}} = -F\_{\text{opt}} = K \times (X\_{\text{sphere}} - X\_{\text{laser}})
= K \times X\_{\text{sphere/laser}}. \tag{3}
\]

The position measurement is obtained by an image projection of the trapped object (or the laser interferences) on the sensor, centered on the optical axis. A laser misalignment with the optical axis directly impacts the projection on the sensors and may cause the working domain to shrink or disappear. How to obtain a precise measurement of relative position (\( X\_{\text{sphere/laser}} \)) over a large domain is a subtle question which requires further discussion.

### C. Measurement techniques

For a good spatial resolution, the direct measurement of the relative position \( X\_{\text{sphere/laser}} \) between laser and the trapped bead is achieved with only one sensor instead of carrying two separate measurements of the laser and bead positions. This purpose is easily achieved with special optical systems (see Figure 5).

The first scheme, using differential position measurement (see Fig. 5(a)), is based on differential interference contrast microscopy: two Wollaston prisms split the trapping laser beam slightly before the sample plane and then combine it again after the sample plane. Two imperceptibly separated beam paths are created near the optical trap. Any disturbance of the trapped object position unbalances the two paths and produces a resulting phase shift on the photodiode sensors. This information is directly correlated to the desired relative position\(^ {63,64} \). Moreover, this interferometric phenomenon has a very good spatial resolution since it is not limited by the laser wavelength. Unfortunately, the optical path provides only a one dimensional measurement and is very sensitive to mechanical noise. The interferometric optics cost and alignment complexity explain why it is barely used now. Other interferometric and alternative techniques are detailed in Table III.

The second interferometric cited method, named “back focal plane,” gives good three-dimensional results for small particles (compared to the laser wavelength). In this case, the scattered part of the laser beam, going through the bead, interferes with the unscattered part.\(^ {20} \) The interference pattern is imaged on the condenser\(^ {51,70} \) or the objective\(^ {71} \) back focal plane (BFP) (see Figure 5(b)). The correlation between the signal and the relative position is well known and a simple quadrant photodiode is sufficient for three-dimensional measurement.\(^ {20} \) Furthermore, telescope optical schemes reduce the sensitivity to trap misalignment (workspace \( \approx 50 - 10 \, \mu \text{m}^{23} \)). This configuration gives good results for closed loop control and artificial trap stiffness tuning.\(^ {51,72} \) It is also used in metrological workbenches, called photonic force microscopes.\(^ {20,48} \)

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**TABLE III.** Comparison of high speed position detection methods. The acquisition and image processing are in frames per second (fps) for cameras and in refreshing rate (Hz) for others.

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Ref.</th>
<th>Dim</th>
<th>Price (K€)</th>
<th>Illumination</th>
<th>Acquisition</th>
<th>Image processing</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferometer</td>
<td>63</td>
<td>1D</td>
<td>€ € €</td>
<td>Laser</td>
<td>100 kHz</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Back focal plane</td>
<td>20</td>
<td>3D</td>
<td>€</td>
<td>Laser</td>
<td>850 kHz</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Photodiode imaging</td>
<td>47</td>
<td>2D</td>
<td>€</td>
<td>Tungsten 100W</td>
<td>2 kHz</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Fast CMOS</td>
<td>65</td>
<td>2D</td>
<td>€</td>
<td>Halogen 100W</td>
<td>2 kfps</td>
<td>Off line</td>
<td>...</td>
</tr>
<tr>
<td>Fast CMOS</td>
<td>66</td>
<td>2D</td>
<td>€</td>
<td>Halogen 50W</td>
<td>2 kfps</td>
<td>0, 5 kHz</td>
<td>Centroid</td>
</tr>
<tr>
<td>FPGA</td>
<td>67</td>
<td>2D</td>
<td>€</td>
<td>Cold LED 15W and optical fiber</td>
<td>10 kfps</td>
<td>10 kHz</td>
<td>Hardware</td>
</tr>
<tr>
<td>Stereoscopy</td>
<td>68</td>
<td>3D</td>
<td>€</td>
<td>2 × white LED 3W and optical fiber</td>
<td>340 Hz</td>
<td>340 Hz</td>
<td>Symmetry recognition</td>
</tr>
<tr>
<td>DVS</td>
<td>69</td>
<td>2D</td>
<td>€</td>
<td>Cold LED 5W</td>
<td>3 kHz</td>
<td>30 kHz</td>
<td>Spare matrix hough circle</td>
</tr>
</tbody>
</table>
However, the two previous solutions are difficult to implement and a simpler scheme is often preferred: object imaging with a white light source or an additional laser beam. This technique is suitable only for big visible objects under an optical microscope to preserve an adequate resolution. The image is commonly acquired with two types of sensors: quadrant photodiode or video cameras. Quadrant photodiodes were the first position detectors. As these sensors only have 4 pixels, their acquisition rate is high (>1 GHz). Higher resolution image sensors allow useful image processing metrics obtained with algorithms such as centroids, histograms, interpolation, and cross-correlation. Information obtained by their numerous pixels is highly valuable to discriminate shapes, impurities, and contacts. Sensor alignment is facilitated by software reallocation of the region of interest (ROI), and image data also allows fine tuning of focus via edge sharpness.

Today, new generations of CMOS cameras allow more than 2000 frames/s for a reduced ROI. For the purpose of optical tweezers, this is sufficient because the relaxation time of the OT phenomena is limited in an aqueous medium by fluid viscosity and trap stiffness; existing system’s bandwidth is therefore often under 1 kHz. Despite the fact that acquisition time is not an issue, computing resources are still not able to achieve complex and robust image processing at this rate. For example, a centroid calculation can be very fast (performed at more than 10 kHz) but it is very sensitive to disturbances such as shadows, contacts, or impurities, and therefore does not provide a reliable and safe force measurement with random experimental conditions. In comparison, the Hough Transform is very robust to track spherical objects, but it is highly time-consuming and so, in this case, not practical. Recent development of vision sensors encourages new high speed tracking techniques. FPGA (Field Programmable Gate Array) or smart cameras perform embedded hardware image processing and allows refresh rates of the position information up to 10 kHz and for two simultaneous bead tracking. A new sensor, asynchronous temporal contrast silicon retina, DVS (Dynamic vision sensors) provides event-based information of the scene and records only intensity changes. It allows software solutions for dynamic event processing at more than 30 kHz. It is important to note that at such high acquisition rates, the temporal resolution meets limitations due to the number of photons which can reach the sensors during the acquisition period. Illumination with a higher light power is necessary.

In summary, existing systems do not satisfy the necessary conditions for good force feedback operations, especially the workspace size and system bandwidth. The recent technologies and their future developments are promising directions to investigate for better teleoperated optical tweezers performances.

IV. SPECIFIC DESIGNS FOR HAPTIC INTERACTIONS

Performance of teleoperated manipulators depends on the latency and speed of the whole system dynamics, adequate degrees of freedom for the manipulation required, and adequate resolution and amplitude of force to mimic normal human interaction with directly tangible objects. The existing optical path designs of OT are insufficient and a new design is needed. There are few existing propositions worth discussing.

Besides, many groups look for collaborative haptic micromanipulation systems (for instance, with 2 hands or 2 users) using these two methods. To achieve multiple traps or degrees of freedom, a laser beam may be separated into multiple traps by division in time or space. In temporally divided trapping, multiple traps are sequentially illuminated at a faster rate than the trapped object’s natural dynamics. In spatially divided trapping, multiple traps can be formed by shaping the laser with grating or holographic interometric methods.

A. Temporal sharing

For fast scanning techniques, new optical schemes must be proposed to overcome the misalignment issues and improve the workspace of the experimental setup. We illustrate this argument with an example from Ref. As Figure 6 shows, placing the sensor on the other side of the deflecting actuator is an easy way to solve the issue. In this manner, the white light reaches and goes through the actuator in the exact opposite direction from the laser beam. Doing so, the image on the sensor is always centered on the laser spot. However, the actuator must have special optical properties: it reflects or transmits light with few aberrations and differently from one side or the other. In other words, it is an optically reversible deflector. Galvanometers are well suited for this purpose, while AOD (see Sec. III A) or SLM are not convenient because of the use of interference patterns.

Using this method, the workspace is now unlimited in the microscope view and meaningful sensations have been perceived. In the work of Padgett and co-workers, shape explorations have been achieved with microprobes (see Figure 7). The edge of a silica MEMS (microelectromechanical systems) corner is perfectly tactually recognizable. Other

FIG. 6. Backward and forward imaging principle. (a) The image is obtained in the back of the actuator on the laser path, (b) the image is obtained in the front of the actuator and stays aligned with the laser deflection. The image area can be reduced to decrease acquisition and processing times. The actuator, here galvanometers, should be reversible, i.e., reflective or transmissive in both ways.
sensations such as viscous drag and Brownian motion are reliably fed back to the user.

With this configuration, the dynamics and bandwidth are good enough for one trap. For several traps, the power must be temporally shared, and the scan frequency must be high enough so that each trap is updated faster than it is natural physical dynamics, i.e., the trapped particle does not notice the discontinuity. In the case of the time sharing technique, only one sensor receives the measurement of all the scanned points. The synchronization between the acquisition time and the standing time of the scanner is just a technical issue. This has already been performed with ultrahigh speed sensors for nine traps without any haptic purpose. The remaining issue to achieve our goal is to find the adequate sensors and processing power for fast and robust measurement.

B. Spatial sharing

Galvanometers however provide only 2D actuation capabilities. For three-dimensional multi-contact grasping, holographic systems like SLM are more elegant. Recent works show an implementation of holographic optical tweezers (HOT) with two force feedback handles. This system uses an enhanced nematic liquid crystal SLM and a fast CMOS camera. The haptic coupling loop rate is only 100 Hz (instead of the recommended 1 kHz) because of SLM and image processing limitations. Moreover, the choice of actuators and command produces an important delay between the user handle motion and the actual laser actuation. This lead to insufficient amplitude of the force feedback due to system instabilities.

Nowadays, faster SLM devices are available. Ferroelectric SLMs can create hologram patterns at up to 1440 Hz. Few implementations have proven the efficiency of this technology up to 1 kHz. The high cost of this components puts off some laboratories. Assuming the fast SLM technologies available, specific force measurement techniques should be developed.

In this case, the trapped objects travel in a large area cannot be tracked with the previous specific optical methods (back focal plane or backward imaging camera, see Figure 6). This reduces the acquisition and processing speed, or the resolution. For example, one of the best proposition comes from Bowman et al. The symmetric properties of the probe that have used are higher level algorithms than a centroid, on the 60 × 60 pixels of the CMOS and succeeded with having a force refreshing rate of 400 Hz.

The bottleneck between fast refresh and high level detection, which are robust to external disturbance, can be solved today by new sensors technologies. For example, the asynchronous retina has a real advantage for increasing precision and speed of force measurements. Sensitive to intensity changes, the desynchronized pixels provide only the useful information about the scene and act as an edge detector (see Figure 8). Pixel events are sent as a continuous flow addressed by hardware timestamps and location. The commercially available sensors have 1 μs clock resolution for 128 × 128 pixels and each pixel has a 3 kHz bandwidth. Specific image processing is performed on an event list which may be seen as a sparse matrix. Highly complex algorithms are implemented with incomparably high speed and low computational resources. Efficient tracking of multiple microspheres with Hough transform methods within 100 μs are performed. As these sensors are in an early state of development, their potential for better pixel resolution, bandwidth, and contrast ratio promises even larger improvement of microscopy applications. For example, some on-going works are focused on multi-trapping, out-of-focus measurements and better haptic sensations (higher resolution, stability, and reliability).

V. DISCUSSION

Looking at these recent developments, interactive micro-manipulators have never been so close to the human hand. A few experimental setups have already displayed reliable and useful feedback. However, more research must
be performed to obtain the full potential of this method. The most important aspects are discussed in this section: z-axis force feedback, stiffness model limitations, advanced trap microtools, and haptic devices.

The trap stiffness is lower along z-axis and as a result bead escape frequently.90 The depth of field of the microscope image (with high numerical aperture objectives <1 μm) is narrow, i.e., objects become blurred when traveling on z-axis. This out-of-focus effect explains why z-axis particle tracking is more difficult than in x- and y-axis in microscopy. For small particles, back focal plane techniques are very efficient thanks to laser interferences dependence on z-axis displacement.48 However, this measurement is not robust to external disturbances (obstacles, impurities). For objects bigger than laser wavelength, other techniques exist such as image processing of the diffraction pattern of the trapped object.91, 92 Another option is to obtain a stereoscopic image with two different light sources:68, 93 the distance between the two projected images of an object is used to determine the relative axial position of the trapped object. Tiny displacements are hence magnified, but the image acquisition and processing must be performed on larger area. Three-dimensional images are also obtained with holographic techniques based on light phase. Custom digital holographic microscopes are under development.94, 95 More research must be carried out to propose satisfactory temporal bandwidth of sensors, algorithms, and imaging sources.

Quantitative force measurement is a delicate subject, because it is based on a model with numerous limitations. OT has proven metrologic capacities24 in a controlled environment. The linear trap stiffness model is only accurate away from obstacles.21 Real interactions bring other issues: uncontrolled environments, impurities, lateral or axial contacts, and particle overlap. In these conditions, the laser is modified by surrounding objects and the optical force model is no longer accurate. More research must be carried out on models for contact conditions and on the influence of impurities. However, because human tactile perception of force is relative, a precise and quantitative value of the force is not necessary for haptics, but disturbances should not alter the sensations while operating.

Different laboratories are developing advanced robot-like micro-tools, which can benefit from a haptic force feedback. These new properties benefit from special materials, such as gels96 or photopolymerized structures93 and from custom structures with several trapping sites.81, 97–99 Doing so, these microtools possess a complex balance of force while interacting with the sample. Force models and measurements are being investigated.99, 100 Those structures are complex to control: additional degrees of freedom such as rotation, parallel traps, rigid or flexible parts. These parameters can be processed by advanced and intuitive interfaces that can merge position and force information on the user hand (see Figure 9).

The master interface system and operator mechanics are interlinked with the slave (micromanipulator) system. Further improvements must be proposed on both sides of the haptic coupling loop to be worth increasing the performance. First, the mechanical bandwidth of commercial haptic interfaces is particularly unsatisfactory and adds instabilities in the haptic coupling loop.103, 104 The second important issue is the inadequacy of existing designs for the specific tasks of micromanipulation: handles shapes, degrees of freedom, and structure are not intuitive for the tasks and collaborative works. Therefore, commercial haptic devices are no longer the optimal choice for the master side, and the micromanipulation

FIG. 8. Dynamic image of two microspheres (3 μm and 11 μm) put into contact. Dots are the events sent by the asynchronous pixels in a 30 ms time windows. The color of the dots depends on the increment or decrement of light intensity on pixels.

FIG. 9. Concept of advanced nimble microtools to explore cells using optical tweezers and haptic force feedback.
community must collaborate with the haptic community to conceive new designs for their specific applications.101, 102, 104

VI. CONCLUSION

This paper summarized the essential points for the construction of an efficient haptic feedback micromanipulation platform. The main idea is to consider the haptic optical tweezers as a whole instead of the combination of two systems. The paper also highlights requirements in term of bandwidth, workspace, and robustness for the complete system.

As human perception of force amplitude is not quantitative and precise, force feedback teleoperation is an efficient solution to display helpful qualitative information of microworld explorations. In our case, the amplitude resolution of the force measurement is a less important specification than the temporal resolution and robustness to disturbances, because the feedback mechanism must be safe and useful.

All things considered, more research and effort are still required to obtain a practical and useful haptic feedback platform. This paper proposes new leads and sheds light on latest joint works and his expertise on vision for microscopy. The potential of this method is huge, particularly, in the field of biomedicine where optical tweezers are in widespread use. The force feedback can reduce the time of operations and increase the feasible complexity of tasks. The new capabilities offered by haptic optical tweezers will inspire study and diagnosis of new types of cells105, 106 or allow complex assembly of biomedical materials.107

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