Haptic Feedback of Piconewton Interactions with Optical Tweezers

Cécile Pacoret[1,2], Arvid Bergander[1], and Stéphane Régnier[2]

[1] Sensory and Ambiant Interfaces Laboratory, CEA LIST, F-92265 Fontenay-ax-Roses, France
[2] Institut des systèmes intelligents et robotique, Université Pierre et Marie Curie, CNRS UMR 72222, F-75005 Paris, France
pacoret@isir.fr, a.bergander@ieee.org, regnier@isir.fr

Abstract. Haptic feedback for micro- and nanomanipulation is a research area of growing importance with many potential applications in micro- and biotechnology. Past research often involves the coupling of atomic force microscopes to haptic devices, but the results are not satisfactory. We propose to adopt a different approach, which consists of contactless manipulation, in particular by using optical tweezers, coupled with a haptic feedback device. In this article, we describe the potential of such a tool and show with some first experiments of stable interactions between micro-particles.

Keywords: micromanipulation, optical tweezers, haptic feedback, bilateral coupling.

1 Introduction

Grasping and placing precisely micro- and nano-parts are still arduous and costly micromanipulation tasks. Haptic force feedback may help greatly to detect contacts, thus allows a control between objects interactions and increases the efficiency and safety of the tasks. But not all usual micromanipulation tools are well suited for coupling with haptic interfaces.

An atomic force microscope (AFM) beam for instance is used to move an object and to measure the interactions thanks to cantilever deflection. The AFM tip seems to be well suited for pushing microobjects, but its large size is disadvantageous. They obstruct the microscope view during manipulation and the adhesion forces are also important on its surfaces and the samples stick to the tip. Even though particular strategies have been developed applying surface treatments or using two tips [1], the haptic rendering is poor and limited to one axis and simple tasks.

Our goal is to show that a rational choice of micromanipulation techniques and strategies may help greatly the haptic perception (see Fig. 2a.). Optical tweezers are a judicious choice for this purpose, they allow a simple coupling which is transparent and stable. In the following we will briefly explain the basic principle, followed by a presentation of the coupling scheme and finally present an experimental setup with first results.

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2 The Micromanipulator Choice

2.1 Microworld Interactions

In the microworld, the weight of micro sized objects is negligible compared to surface effects. Consequently inertia is insignificant and acceleration is very high. The objects are subject to different interactions : adhesion, electrostatic forces and viscous drag in liquid. Miniaturized tools like micro-grippers or AFM cantilever have a large surface compared to the handled object and thus surface interactions are big which means large adhesion forces.

Other techniques seem to be better suited, which is why ”contactless” techniques begin to hold the interest of the research community [2]. Many micro-tools are airborne and employ effects of potential fields. Electromagnetic tweezers [3] and optical tweezers [4] allow a three-dimensional control respectively of a magnetic bead and a dielectric bead in liquid medium only. Contactless manipulation can be used directly without any adhesion effects, but the trap beads are also used to indirectly manipulate random shape objects. A contact occurs in this case between the small trapped micro-tool and the sample, with small adhesion effects.

As the interactions between a trapped micro-tools and the indirectly manipulated sample can be measured, it is interesting to feed back them to the operator. We have selected optical tweezers as manipulator, because, in water, the dynamic is damped and the interactions are scalable and interpretable for the human range. Secondly, the most delicate operations are in the domain of biology where optical tweezers are widespread.

2.2 Laser Manipulation Flexibility

Optical tweezer with force-feedback have been investigated in the past. Arai realizes an experiment with real force-feedback on a trapped particle in a liquid medium free of obstacles [5]. Basdogan proposes a virtual haptic guidance to help the docking of particles [6]. In this paper, we will show the full potential of this flexible tool using a real force feedback when the trapped particles encounter an obstacle thanks to our stability improvements.

Optical tweezer’s properties come from the laser source. The light going through a spherical object produces a force. If the bead’s refractive index is superior to the environment one, the bead is trapped on a convergent laser focal point. Using a high numerical aperture microscope objective, researchers build since 1986 [7] powerful traps to displace nano- and micro-objects like cells [8], viruses and crystals.

Multiple traps allow more complex applications like holding directly nanowires, microfabricated tools [9], or indirectly random shaped objects [10]. In that case, fast beam deflectors (scanners, acousto-optical-deflector) or diffractive actuators (spatial light modulator, SLM) may be used and coupled to multiple haptic interfaces for a collaboration of the two hands, fingers or more than one operator.

Optical tweezers also have good properties for visual control of the manipulation : they are small and do not disturb the manipulation view. Moreover, they are compatible with other optical microscopy allowing three-dimensional view or DNA visualizations (confocal and fluorescent microscopy [8]).

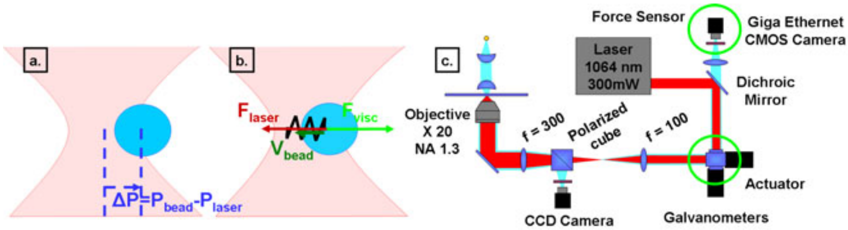

Fig. 1. a. Spring-damping model of the optical trap. **b.** Force balance on an optical tweezers trapped bead. F_{laser} and F_{visc} are respectively the optical force and the viscous drag. V_{bead}, P_{bead}, ΔP and P_{laser} are respectively the speed, the displacement of the bead, its relative position to the laser and the laser position. **c.** Laser and light optical path. The laser beam (pumped Ytterbium fiber, 1064 nm) is deflected by galvanometers (Cambridge technology, Inc), oriented by a telescope to a high NA objective (Olympus, x40, NA. 1.3). A first video camera shows the scene and a second high speed video camera (Dalsa CMOS, 1000fps for 80×80 pixels) is used for position measurements process by a custom C++ program.

2.3 Force Measurement

Optical tweezers are also precise force transducers. The literature [4] describes abundantly the properties of their model : the trap behaves like a three-dimensional spring. To obtain the force applied on the trapped object, a measurement of the relative position of its center to the laser spot is sufficient (see Fig. 1a.):

$$F_{laser} = -K \cdot (P_{bead} - P_{laser}) \tag{1}$$

where K is the trap stiffness, F_{laser} the optical force, P_{bead} et P_{laser} respectively the object and the laser positions. Interferometer, photo-detection or video image processing may be used as position detector and the calibration of the trap stiffness may be obtained with the viscous drag model or the power spectrum method [4]. The calibration errors are not critical for the haptic sensation, as we will see the stiffness can be integrated in the force gain of the direct coupling (see section 3.1). In fact, the laser force measurement gives an image of the other external forces (F_{micro}) as the force balance shows. The dynamics effects are negligible thanks to the object size (see Fig. 1b.):

$$F_{laser} + F_{micro} = M_{bead} \cdot \ddot{P}_{bead} \approx 0 \implies F_{micro} = -F_{laser} \tag{2}$$

Using this equation, the force fed back to the operator by means of an haptic interface is the opposite of the measured laser force. Viscous drag and obstacles such as the surface of a micro channel, larger micro objects or even the Brownian motion due to thermal effects can thus be haptically rendered.

3 Direct Coupling for Good Stability and Transparency

3.1 Non-contact Micromanipulation and Coupling

Our optical tweezers installation (see Fig. 1.c.) includes a laser (1064 nm), an actuator that deflects the light beams (galvanometers), a telescope and an high numerical aperture objective (NA = 1.3). White light is used to image the bead on an high speed video

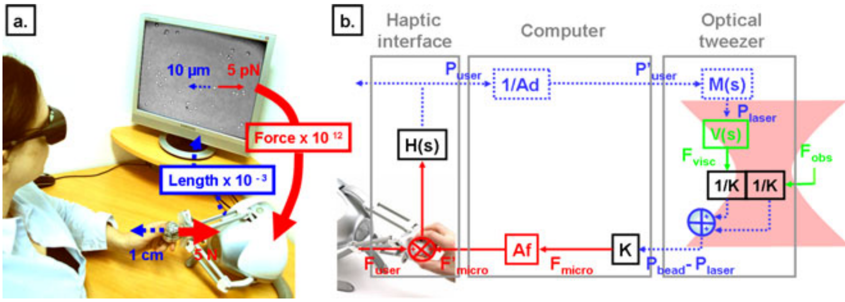

Fig. 2. a. Concept of haptic micromanipulation. **b.** Automatic scheme of the direct coupling between the optical tweezer in Laplace formalism : H(s), M(s) and V(s) are respectively the transfer function of the haptic interface, of the actuated mirrors and of the viscous model. K, Ad, Af are respectively the trap stiffness, the position gain and the force gain.

camera. This sensor is centred on the laser beam thanks to optical path design and allows a direct measurement of the bead's relative position. Using the stiffness model, the force is obtained from this position detection.

This particular design and the chosen high speed components (galvanometers and the triggered fast image processing system) allow the actuation and the position detection of two or three beads. Moreover, the good performances of this tool are an advantage for the stability of closed loop system.

Haptic coupling is a close loop system and benefits of delay optimisation of its components. Even if the optical tweezer was linked to a low cost commercial haptic interface (Falcon by Novint), a direct coupling was used without instabilities. The coupling links consist of simple homothetic gains : in position, Ad and in force, Af (see Fig. 2a.). They are chosen in a way that the handle displacements match optical tweezer workspace and microworld amplified forces are perceptible by human hand (> 1N). This coupling method is the most transparent, but may lead to instabilities which can be very important in the case of "contact" micro-manipulator [11].

To prove it, we study the closed loop stability of the coupling (see Fig. 2b.) by applying the Routh-Hurwitz criterion. For the trap stiffness (10^{-7} N/m), object dimensions (R=$2 \cdot 10^{-6}$ m) and viscous drag ranges ($6\pi \cdot \mu_{water} \cdot R$), the system remains stable for large homothetic gains. For $Ad = 10^4$ (centimeter convert to micrometer), the force gain may safely be set to $Af = 10^{12}$, which allows piconewton perception.

3.2 Experimental Proof

In order to improve system response speed [12] and the transparency, we build a dedicated optical tweezer installation. Fig. 3a. shows its response to two constant speed ramps. The viscous drag sensation is highlighted and proportional to speed: the user feels a bigger mechanical resistance as he moved the handle faster. Small oscillations on this curve are the random noise characteristic of the Brownian motion on the trapped bead.

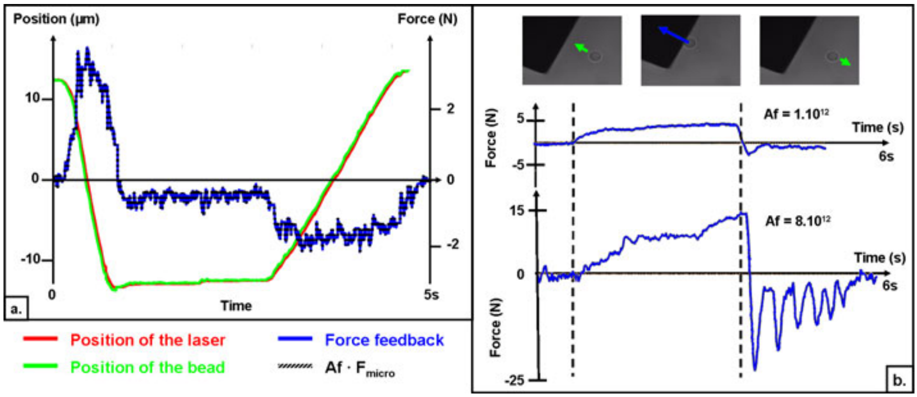

Fig. 3. a. Response of the system to constant speed ramps ($Ad = 10^4$, $Af = 2 \cdot 10^{12}$). The displacement of the laser (blue), of the bead (green) and of the haptic interface (scaled, purple) are presented in comparison with to feedback forces in Newton (blue). **b.** Response of the system to a wall contact. The user force feedback is shown for different force gains : in the first graph $Af = 1 \cdot 10^{12}$ and in the second graph $Af = 8 \cdot 10^{12}$ ($Ad = 10^4$).

In order to prove that the system remains stable in presence of an obstacle, we push a 5 μm bead on the wall of a 100 μm silicon cube. The first graph of Fig. 3b. show the force feedback to the user for a force gain of $1 \cdot 10^{12}$. The sensation of contact is efficient, the user does not push more than necessary to feel the wall. He can pull the bead away with a transparent sensation of the damped dynamic.

The second graph, in contrast, shows what happens if the force gain is higher. Sudden change of ΔP results in a damped oscillation. This situation must be avoided for the manipulation comfort and safety. Optimising our system for better stability allows us to keep it safe from resonant mode of the direct coupling scheme till the precision range of piconewton perception ($2 \cdot 10^{12}$).

4 Conclusion and Perspectives

In this paper, we have presented a system for haptic micromanipulation based on optical tweezers. The high degree of transparency achieved thanks to the stable direct coupling is an important improvement for this contactless micromanipulator. The two coupling parameters are easy to tune and the high force gain allows good haptic perception of piconewton forces even in the exploration of an obstacle.

Optical tweezers are widespread in biology laboratories and the study of single molecules or cells may benefit from the feedback of force information to the operator's hands. They are also affordable [13] for undergraduate pedagogical projects, and the force feedback may help understanding microworld phenomena.

First experiments show already the potential of these flexible tools. A three-dimensional force feedback system is possible with holographic actuator (SLM) and confocal technology. We focus our future work on the multi-trap force feedback and work on user studies in order to highlight the efficiency of this instrument.

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