Touching the microworld with force-feedback optical tweezers

**Cécile Pacoret [1,2,†,*], Richard Bowman[3,†], Graham Gibson[3],
Sinan Haliyo [1], David Carberry[4], Arvid Bergander [2],
Stéphane Régnier[1] and Miles Padgett[3]**

[1]*Institut des Systèmes Intelligents et Robotique (ISIR), Université Pierre et Marie Curie - Paris 6/CNRS, 75005 Paris, France.*
[2]*CEA LIST, Laboratoire Interfaces Sensorielles, 92265 Fontenay-aux-Roses, France.*
[3]*Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK.*
[4]*H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK.*
[†]*These authors contributed equally to this work.*
[*]*pacoret@isir.fr*

Abstract: Optical tweezers are a powerful tool for micromanipulation and measurement of picoNewton sized forces. However, conventional interfaces present difficulties as the user cannot feel the forces involved. We present an interface to optical tweezers, based around a low-cost commercial force feedback device. The different dynamics of the micro-world make intuitive force feedback a challenge. We propose a coupling method using an existing optical tweezers system and discuss stability and transparency. Our system allows the user to perceive real Brownian motion and viscosity, as well as forces exerted during manipulation of objects by a trapped bead.

OCIS codes: (140.7010) Laser trapping; (150.5758) Robotic and machine control; (350.4855) Optical tweezers or optical manipulation.

References and links

1. A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles," Opt. Lett. **11**, 288–290 (1986).
2. G. Whyte, G. Gibson, J. Leach, and M. Padgett, "An optical trapped microhand for manipulating micron-sized objects," Opt. Express **14**, 12497–12502 (2006).
3. J. Grieve, A. Ulcinas, S. Subramanian, G. Gibson, M. Padgett, D. Carberry, and M. Miles "Hands-on with optical tweezers: a multitouch interface for holographic optical trapping," Opt. Express **17**, 3595–3602 (2009).
4. E. van West, A. Yamamoto, and T. Higuchi, "The concept of "Haptic Tweezer", a non-contact object handling system using levitation techniques and haptics," Mechatronics **17**, 345–356 (2007).
5. C. Basdogan, A. Kiraz, I. Bukusoglu, A. Varol, and S. Doğanay, "Haptic guidance for improved task performance in steering microparticles with optical tweezers," Opt. Express **15**, 11616–11621 (2007).
6. I. Bukusoglu, C. Basdogan, A. Kiraz, and A. Kurt, "Haptic Manipulation of Microspheres Using Optical Tweezers Under the Guidance of Artificial Force Fields," Presence **17**, 344–364 (2008).
7. F. Arai, M. Ogawa, and T. Fukuda, "Indirect Manipulation and Bilateral Control of the Microbe by the Laser Manipulated Microtools," Proc. IEEE **1**, 665–670 (2000).
8. G. Gibson, J. Leach, S. Keen, A. J. Wright, and M. J. Padgett, "Measuring the accuracy of particle position and force in optical tweezers using high-speed video microscopy," Opt. Express **16**, 14561–14570 (2008).
9. A. Berthoz, *The Brain's Sense of Movement* (Harvard University Press, 2000).
10. L. Ikin, D. Carberry, G. Gibson, M. Padgett, and M. Miles, "Assembly and force measurement with SPM-like probes in holographic optical tweezers," New J. Phys. **11**, 023012 (2009).
11. A. Bolopion, B. Cagneau, D. S. Haliyo, and S. Régnier, "Analysis of stability and transparency for nano force feedback in bilateral coupling," J. Micro-Nano Mech. 10.1007/s12213-009-0016-3 (2009).
12. S. Keen, J. Leach, G. Gibson, and M. Padgett, "Comparison of a high-speed camera and a quadrant detector for measuring displacements in optical tweezers," J. Opt. A: Pure Appl. Opt. **9**, S264–S266 (2007).

#110312 - $15.00 USD Received 20 Apr 2009; revised 29 May 2009; accepted 2 Jun 2009; published 4 Jun 2009

13. M. Goldfarb, “Dimensional Analysis and Selective Distortion in Scaled Bilateral Telemanipulation,” Proc. IEEE **2**, 1609–1614 (1998).

---

1. Introduction

Optical Tweezers [1] have become a widespread tool in Cell Biology, microengineering and other fields requiring delicate micromanipulation. Most tweezers systems use a mouse or a standard joystick to control the optical trap. Although more complex methods of position control have been tried [2, 3], force feedback has been relatively unexplored. Force feedback remote handling is an advanced technique to improve the user’s dexterity for delicate tasks, and has already shown its effectiveness in nuclear energy and surgery. Moreover, optical tweezers are routinely used for force measurement, which could be relayed to the user. Van West suggested in 2007 the concept of “haptic tweezers” for non-contact micromanipulation using magnetic levitation [4]. Within optical tweeers, haptic interfaces have been shown to help guide the user in following a path [5] and avoiding collisions [6] by using an artificial force field. This “haptic assistance” proves it is useful, though it does not allow the user to feel the forces actually experienced by the particle. Previously, Arai *et al.* [7] demonstrated a limited use of forces measured using a quadrant photodiode within an optical tweezers to create force feedback in response to motion of the sample stage. However, in this last paper the ergonomics of the interface, the scaling problems (see Fig. 1), the stability of the coupling and the transparency of perception have not been examined. We describe the principle and the problems of force feedback remote handling for the microworld, and our implementation using measured forces in optical tweezers. An existing optical tweezers system is coupled to a low-cost commercial haptic interface, Falcon by Novint. The forces acting on the bead are measured using a high-speed video camera [8]. It is placed in the back reflected optical path behind the trap steering mirror and is therefore robust to the environment and delays in steering the trap. We then explain the aspects of the system’s performance required for effective coupling. Finally, several experiments prove the principle and outline the achievable sensations.

Fig. 1. Scaling factors between the microworld and the macroworld (filled arrows), and the distortion of dynamic parameters which follows by dimensional analysis (hollow arrows).

2. Force feedback remote handling for the microworld

Everyday tasks are possible thanks to our ability to see and touch. The collaboration of our senses is essential, since vision outlines the trajectory and touch achieves precision in critical assemblies. Moreover, the sense of touch is much more responsive, able to resolve information at up to 1 kHz instead of 24 Hz for vision [9]. In addition microscope images are only 2D and some objects remain invisible in standard optical microscopy (DNA, nanotubes, etc.)[10]. Therefore, touch is crucial for improving manipulation in the microworld. Force feedback remote handling allows us to recover the mechanical link for touch perception.

This technique implies the use of 2 robots, a slave and a master, in our case respectively the optical tweezers and the 3 axis force feedback device. The information passed between

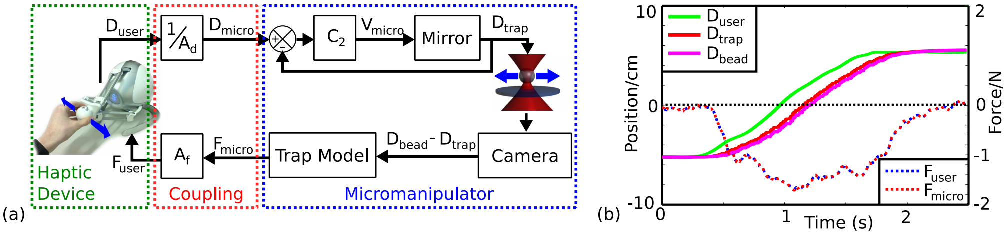

Fig. 2. (a) Schematic of our system, using direct bilateral coupling. D_{user} and D_{micro} are respectively the displacement of the user's hand and the position set point of the laser. $D_{\text{bead}} - D_{\text{trap}}$ is the deviation of the bead from the trap centre and V_{micro} is the mirror speed command. F_{micro} and F_{user} are the estimated forces exerted on the object by the environment and the force feedback to the user. (b) Response of the system to a motion of the controller at a constant speed. Our mirror lags behind the desired trajectory by 200ms, and for a 5μm bead, the delay behind the trap is 50ms. The two force curves match exactly, showing good transparency in force. Microworld quantities have been scaled to macroworld units.

these two systems needs to be transformed (Fig. 1). The "coupling" is this bilateral link (see Fig. 2(a)), here we used constant scaling factors, but other schemes exist [11]. In our installation, the force measurement on the slave is used to create the sensation of touch on the master. A camera or a quadrant photo diode tracks the position of the trapped object [8, 12]. It is hence possible to calculate the force applied to the object using an analytical model of the trap stiffness. A scaled image of these interactions is fed back as a force on the operators hand by the motorized axes of the haptic interface. The ball-shaped handle gives the illusion of touching the microsphere we are trapping, which is very intuitive for our application. The position of this handle is scaled and used to control the position of the optical trap.

An interesting issue is the user's perception of the microworld, where interactions are very different from conventional macroworld mechanics. On the metre scale, bulk forces like mass and inertia are the most important effects. On the micron scale, optical forces, viscosity, adhesion forces and Brownian motion are the predominant forces on trapped objects. Because the dynamics of the two systems are different, there will be stability problems: deviations between the systems will increase instead of converging to zero, and the system will start to oscillate.

Another factor is distortion of the environment [13]. The differences between the scaling factors (shown in Fig. 1) for position and force cause distortion of the perception of the environment. Therefore, stiffness and viscosity are percieved as stronger than they are relative to displacements and weight effects are even more negligible in the perception as it is not scaled like other effects.

Since the scaling factors have high values, the system is extremely sensitive to perturbations and delays. The significant criteria defining the performances of the complete system are the response times of actuators and sensors and the frame rate of the coupling loop. In contrast with previous studies [7], this paper reports the different advantages and limitations of the system in terms of stability and perception. Both hardware and software solutions are discussed.

3. Experimental configuration

Figure 3 shows a schematic representation of the experiment. Trapping is achieved using a CW Ti:sapphire laser system (M^2, SolsTiS) which provides up to 1.3W at 830nm. This is steered using a computer-controlled, micrometer driven mirror allowing us to position the trap anywhere within the field of view. The tweezers are based around an inverted microscope, where the same objective lens, 100x 1.3NA, (Zeiss, Plan-Neofluor) is used to both focus the

#110312 - $15.00 USD Received 20 Apr 2009; revised 29 May 2009; accepted 2 Jun 2009; published 4 Jun 2009

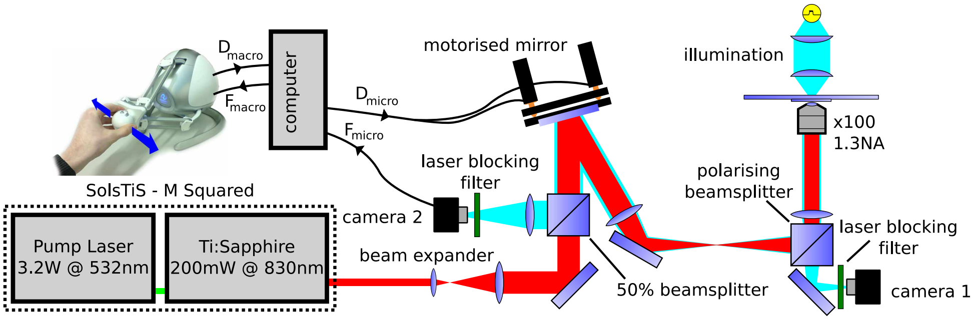

Fig. 3. The tweezers system is based around an inverted microscope. The laser beam is steered by a computer-controlled mirror, providing one trap with a power of approximately 30mW. Camera 1 images a 60μm wide area of the sample, while camera 2 takes high-speed images centered on the optical trap for particle tracking and force measurement.

trapping beam and to image the resulting motion of the particles. Samples are mounted in a motorized microscope stage (ASI, MS-2000).

Two CMOS cameras are used to view the sample, with bright-field illumination. One is in the traditional location (immediately after the objective and tube lenses and therefore unaffected by the beam steering optics), and provides a wide field of view to see the experiment (Prosilica EC1280, camera 1). The other (Prosilica GC640M, camera 2) uses a reduced region of interest to take high speed images.

The position of camera 2 behind the beam steering mirror means that the trap will always be in the centre of the camera, and the workspace is limited only by the field of view of the microscope. Thus, by measuring the deviation of the particle position from the centre of the image, we can measure the force without knowing the position of the trap exactly. This makes the force measurement insensitive to position error and latency in the mirror control system. Positioning the camera behind the steering optics makes force measurement simpler and faster, and permits a larger workspace compared to a quadrant photodiode or a camera in the traditional position. CMOS technology allows us to capture a 50 pixel (7 μm) image at 1kHz. This can be analysed on-line using our own LabView (National Instruments) software running on a standard desktop PC, providing force measurement with the bandwidth we require for transparent force sensation.

4. Coupling the microworld to the macroworld

The fundamental part of the touching sensation is the coupling. Direct bilateral coupling creates a simple loop (see Fig. 2(a)) between the master and the slave elements. The position of the falcon is scaled with the position gain A_d. The optical tweezer receives this information and connects it with the position of the laser. Then the interactions are measured with the camera, adapted with the stiffness calibration and scaled with the force gain A_f. This vector is directly used by the haptic interface to produce the touching sensation (up to 9N for the Novint Falcon). As the optical tweezers system is planar, we just use the X and Y axis of the controller. Those scaling gains are determined by considering the position range of the Falcon (12cm) and the magnitude of forces we can perceive (above 1N): $A_d = 4067$, $A_f = 10^{12}$.

In order to evaluate the system performance, we analyse each part of the system. First are the homothetic gains of the direct coupling. A reliable criterion to evaluate the stability is the passivity. A passive coupling does not add energy inside the loop, i.e. the haptic interface only resists the user's motions and does not drive them. Passivity is a sufficient condition for stability

#110312 - $15.00 USD Received 20 Apr 2009; revised 29 May 2009; accepted 2 Jun 2009; published 4 Jun 2009

and it is easier to evaluate algebraically since the condition for a direct coupling is $A_d = A_f$. As our gains are very different, the direct coupling makes the system potentially unstable t[11].

Other factors that can degrade the performance of the system are delays (see Fig. 2(b)). In order to maintain a stable, transparent system the control loop must run at a high speed and reducing latency was crucial. We optimised our software to run the loop consistently at 1kHz, giving smooth sensations and aiding stability. The greatest remaining lag in the system is due to the mirror; communication can not be established faster than about 50Hz. The delay of the mirror limits the range of force gains for which the system is stable, though this could be further improved with faster mirrors. The transparency of the interface to force is excellent, as the force sent to the haptic controller is simply an amplified version of the measured force. Consequently, the two force traces in Fig. 2(b) overlap exactly. The slight deviation between the desired and actual positions of the trap affects the transparency in position, but the difference is only about one bead diameter when moving with an average speed of $7\mu\mathrm{m\,s}^{-1}$, so the system was still easy to use.

To ensure stability, energy introduced by the coupling scheme should be dissipated in another part of the system. Advantageously, optical tweezers are highly suitable micromanipulation systems for bilateral coupling. Because the microworld environment is water, viscous drag on the trapped particle damps the system. Stability analysis allows us to quantify the range of scaling gains and, as for AFM micromanipulation [11], it can help us improve performance. Using simple model of the system (a second order system for the mirror, a linear spring for the trap, constant viscosity), Laplace Transforms and a block diagram like Fig. 2(a), a study of the closed loop stability shows that the force gain can theoretically be as high as 4×10^{11} in our conditions. Experimentally, we found that a force gain of 10^{12} was stable, but increasing this to 4×10^{12} caused instability. The force gains used are sufficient to have good perception of the forces involved in the micromanipulation tasks.

5. Results

We performed several tasks using our force-feedback system, using a 5μm bead trapped with a stiffness of about $10^{-6}\,\mathrm{N\,m}^{-1}$. The trap was calibrated using the equipartition method [8]. First, we interacted with some silicon cubes, 100μm across. Fig. 4(a) shows the path taken by the bead and the force acting on it as it was pushed around the corner of a cube. The system allowed intuitive perception of the reaction force when the bead was in contact with the cube, and of the viscous drag when it was moved through the water. Without feedback, this task is difficult: the bead often escapes from the trap or encounters adhesion on the corner. With force feedback, those problems are greatly reduced.

To demonstrate the improvement in dexterity due to haptic feedback, we used a simple task: the bead was moved into contact with a cube then pushed along the edge for 20μm, attempting to maintain a constant force. This was performed ten times each with haptic feedback and with only visual feedback, and we recorded the force applied against the cube every 100 ms during the task. Haptic feedback resulted in the bead escaping from the trap less often, so two attempts have been discarded due to failing the task with only visual feedback. The remaining eight trials resulted in a total of 1600 data points each, which are shown in Fig. 4(b). Haptic feedback enabled better precision in maintaining a constant force during each repetition of the task. A complete evaluation is out of the scope of this paper.

As an example of micromanipulation, 5μm beads were used to explore the surfaces of pieces of chrome. Haptic feedback made it very clear when contact had been made with the surface, and enabled precise control of the force applied through the bead. One example was a chrome fragment with a crack into which a bead could be inserted, shown in Fig. 4(c). Locating the entrance of the crack was made simpler by haptic feedback as the bead could be felt slotting

#110312 - $15.00 USD Received 20 Apr 2009; revised 29 May 2009; accepted 2 Jun 2009; published 4 Jun 2009

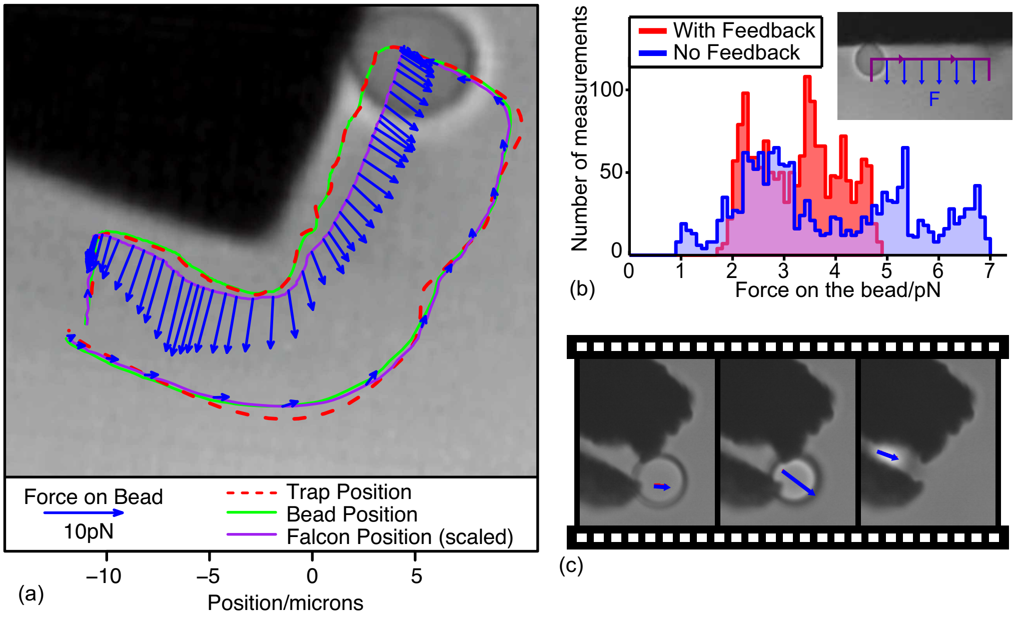

Fig. 4. (a) A bead is pushed along the edge of a silicon cube, maintaining contact as it moves. The force acting on the bead is shown as arrows, at 130ms intervals (Media 1). (b) Histogram showing the force applied to a wall as the bead was moved along it, trying to maintain a constant force. The path followed (line) and force on the bead (arrows) are shown in the insert. (c) Frames from a video sequence showing a 5μm silica bead "docking" with a crack in a piece of chrome (Media 2).

into place. Haptic feedback also made it possible to apply just enough force to insert the bead, without applying any more than was necessary. This is especially relevant to micromanipulaion to avoid adhesion, and to microassembly, where the forces involved are often important to position parts correctly.

6. Discussion and conclusions

We have demonstrated an effective and natural haptic interface for optical tweezers, using a high-speed camera behind the steering mirror for force measurement. This enables an intuitive understanding of microworld forces, as the user can readily perceive real interactions, such as Brownian motion, viscous drag and contact forces from solid objects. The viscosity inherent in manipulating objects in water provides damping which makes the direct coupling stable and transparent. More intelligent coupling schemes could improve on this by accounting for system lag or maintaining stability over a wider range of gains. Force feedback based on measured forces enable a higher dexterity and efficiency than without force feedback, showing that force feedback remote handling is a promising technique for making optical tweezers more flexible, easier to use and accomplishing increasingly complex tasks in the microworld.

Acknowledgements

We thank Prof. A. Walton from the School of Engineering and Electronics, Edinburgh University for fabricating silicon micro-cubes and COST for funding a short term scientific mission.