Touching the Micron: Tactile Interactions with an Optical Tweezer

Stuart Lamont[1] stuartalamont@gmail.com

Richard Bowman[2] r.bowman@physics.gla.ac.uk

Matthias Rath[1] matthias.rath@tu-berlin.de

John Williamson[1] jhw@dcs.gla.ac.uk

Roderick Murray-Smith[1] rod@dcs.gla.ac.uk

Miles Padgett[2] Miles.Padgett@glasgow.ac.uk

1. School of Computing Science, 2. School of Physics, University of Glasgow, G12 8QQ, Scotland.

ABSTRACT

A tablet interface for manipulating microscopic particles is augmented with vibrotactile and audio feedback.The feedback is generated using a novel real-time synthesis library based on approximations to physical processes, and is efficient enough to run on mobile devices, despite their limited computational power. The feedback design and usability testing was done with a realistic simulator on appropriate tasks, allowing users to control objects more rapidly, with fewer errors and applying more consistent forces. The feedback makes the interaction more tangible, giving the user more awareness of changes in the characteristics of the optical tweezers as the number of optical traps changes.

ACM Classification Keywords

H.5.2 User Interfaces: Input devices and strategies

Author Keywords

Tactile feedback; optical tweezers; real-time synthesis.

INTRODUCTION

We apply developments in mobile multimodal feedback design [3, 12] to augment the tablet controller of an Optical Tweezer, described in [2], by augmenting the visual and touch-based interaction with vibrotactile and audio feedback. These feedback the level of force control users have over the microscopic objects being manipulated, allowing them to better control their finger movements. We also introduce an optical tweezer simulation for training and interaction design.

Optical Tweezers

Many areas of science and engineering are increasingly concerned with micro- and nanometre length scales. The ability to manipulate microscopic objects is, therefore, an important tool in fields ranging from biology to nanofabrication. This can be achieved by passing a tightly focussed laser beam through a small transparent object, where any deflection of the light results in a change in the momentum carried by the beam. This change in momentum results in a force which, for most objects, acts to pull the object towards the focal point of the beam (hence the name 'trap'), and was first used to manipulate micron-sized objects by Ashkin [1]. This technique has been extended and refined to make precise force and displacement measurements [7], providing important insights into biophysical problems such as muscle motors and DNA dynamics [7]. Holographic Optical Tweezers (HOT) [9], provide an extension of this technique which uses diffractive optics to provide interactive 3D control over multiple particles [5].

MobileHCI'12, September 21-24, 2012, San Francisco, CA, USA.

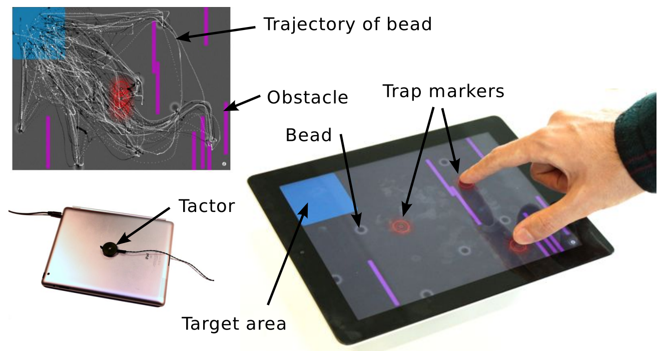

Figure 1: a) Running an experiment with the simulator on a tablet, with a user manipulating particles. b) Plots indicating user behaviour in one of the experiments.

Interaction challenges

Guiding several particles dynamically, simultaneously along trajectories is a non-trivial problem, not easily solved with a mouse or joystick based interface. Multi-touch tablets or surfaces allow the user to simultaneously manipulate multiple particles, overcoming a limitation of mouse-based interfaces. The tablet form factor used here is more convenient and affordable than the previously-used table [4]. However, as the number of optical traps increases, each trap becomes weaker, leading to an increased lag in movement, and an increased likelihood of dropping the trapped object, if moved too rapidly. As the tablet's touch interface is an absolute position interface, where the finger obscures the object in the trap, it is important to consider designs which provide appropriate feedback to the user to allow them to control the system efficiently.

The issue of occlusion in touch interaction is well-known in mobile HCI, e.g. [11], but the challenges in this application differ from the typical occlusion problems in HCI. In the optical tweezer application, users are often dragging several objects in traps to a particular location, in order to create a specific geometric structure, where they are focussed on the goal, and potentially on avoiding obstructions on the way. The dynamics of the individual traps varies rapidly as the number of traps changes, and it is relatively easy for the user to pull too fast and drop the contents of one of the traps, but only to discover this several seconds later, when they arrive at the goal. Offsetting the selected trap would not improve the matter.

FEEDBACK DESIGN

The feedback design is aimed at making the system easier to learn, reducing the number of errors occurring in use, and speeding up performance. When a user has trapped an object on the tablet, their finger obscures the visual feedback, making it difficult for them to control their behaviour as they move to drag the object away. To support the user, we generate audio and vibrotactile feedback that are a function of the user's movement velocity, the strength of trap, and the relationship between trap and objects, i.e. it is modelled around the physical attributes of the particles during manipulation. If multiple traps are controlled, the sounds are the same for each, in this implementation. The audio and vibrotactile feedback is presented via an EAI C2 Tactor[1] taped to the centre of the back of the tablet, and a stereo line splitter allows the separation of audio and tactile signals. Users could hold the device in their hands as normal. The physical insight of the equations of motion of particles affected by traps informed the design of the vibrotactile and audio feedback. In fig. 2 we show the time-series of states, and the vibrotactile response.

Feedback is only provided when a user-controlled trap is interacting with a particle. The feedback is based on all three dimensions. Three different real-time sound models were used to supply the user of the tablet interface with auditory feedback while controlling the optical probe. When objects are moved on the screen a sliding/scratching sound is generated, as of a small solid object sliding on a rough hard surface. This sound depends in every instant on the velocity with which the object is being moved. If the user has tried to move an object too quickly so that it drops, the sound of a falling object such as a light plastic cup is synthesized. The velocity of the user's movement in the moment of the "accident" is mapped to the height or, equivalently, initial velocity of the modelled falling object such that faster movements result in sounds of a cup falling from larger heights (or larger initial impulse).

It is likely that prior to a user's attempt at manipulating the system, they will have a poor intuition about the laser's capabilities in terms of manipulation potential (as this depends on the number of traps already selected), resulting in attempts to move a particle too quickly, with the consequence of dropped particles. They tend to move slower than optimal, wasting resources and reducing work throughput. To persuade users to stay within a safe speed range, while still maintaining the highest possible throughput, a third type of feedback is used. When the user taps on an object on the tablet a short ringing sound, as of a small metal bell, is synthesized, and the tone is adjusted as a function of trap strength. As more traps are added to the interface, the strength of each trap weakens. This feedback is generated regardless of the presence of a particle in the trap or not, so before the user performs any action on the particles, they are inherently aware of the laser's current particle manipulation capabilitites.

[1] http://www.eaiinfo.com/PDF Documents/C-2 tactor.pdf

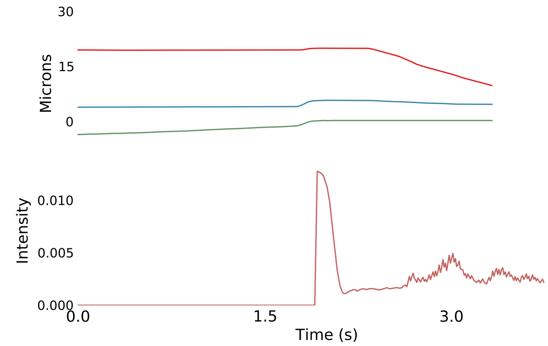

Figure 2: State evolution (x, y, z) of a particle being trapped, then at 2.25s following as the user drags the trap. The lower plot shows the intensity of the vibrotactile response.

SYNTHESIS OF FRICTION AND IMPACT EFFECTS

All auditory feedback in this tablet interface is generated by means of a real-time sound synthesis engine which can generate everyday impact and friction responses, rather than by playing back recorded sound files. The use of real-time synthesis was chosen, as it provides the potential to provide rich real-time feedback about the continuous states of the controlled system. The main technique used in synthesising the sound feedback is known as "modal synthesis" and has been used for the modelling of environmental sounds [6, 10, 8]. It allows us to characterise resonant behaviours, e.g. of vibrating solid objects such as the metal bell or the sounding cup used in the tablet interface in this paper, by means of a set of resonant frequencies and according decay times, or, equivalently, Q-factors. Implementation takes the form of a second-order IIR filter for each considered mode of vibration. For simple but efficient sound behaviours, such as the ones used in the present interface, even a couple of modes can be sufficient. The overall computational cost of these sound models is therefore relatively low.

While modal description can often be used very successfully to model vibration around an equilibrium, such as for elastic deformation of a solid object that is not extremely and enduringly deformed, generally additional techniques are needed to model interactions between two or more objects. In the present sound models, the contact forces in sliding, dropping and hitting are generated as statistical patterns of impulses; in the case of sliding contact the interaction force also includes a continuous component of bandlimited noise. This approach is very similar to the one used in *Phya* [6] where, however, the impulse patterns are for the most part generated by (or an the basis of information from) a game physics engine external to the sound engine. For mobile devices, as the use of such physics engines is neither inherently necessary nor appropriate, interaction forces have to be modelled "from scratch" as part of the sound engine. The generation of the impulse and noise patterns adds only minimal computational effort so that the overall sound generation algorithm remains sufficiently lightweight to be used as part of a user interface on a mobile device. Synthesising sound feedback in real-time generates more richly varied feedback and saves memory and sample acquisition effort when parameterising a wide range of responses.

The key aspect of the synthesis approach is that it inherently supports instantaneous reactivity of sounds reflecting the dynamics of the control interaction. In the current case, the sliding sound directly reflects the momentary velocity of the user's control movement, which cannot be perceived due to the occluded target, and the perceived height of the dropping sound provides the user with feedback about the excessive speed of movement that lead to the error. The ringing sound on acquiring a trap provides feedback about the potential force that can be applied by that trap.

SIMULATION ENVIRONMENT FOR DESIGN

The tablet interface is usually coupled directly to a microscope, but one innovation in this paper is the development of a realistic simulation environment as a convenient way of training new users, and testing the interface in a consistent manner. Optical tweezers are typically used to manipulate micron-sized particles in a fluid, and thus the motion of a trapped object is usually governed by three forces: the spring-like force pulling it towards the trap, viscous drag from the fluid and random thermal motion caused by collisions with the molecules of the fluid. Inertia is not an important effect at this length scale, thus the system is overdamped by the fluid (usually water) in which the particles are manipulated. Simulating the behaviour of optically trapped particles is thus relatively simple.

The important quantities are the positions of the beads and optical traps; we denote the position of the ith bead as x_i and the jth trap as $x_{\mathrm{T}j}$. The collisions of molecules of the fluid with our particle give rise to a fluctuating force ζ which, on millisecond timescales, is a Gaussian random variable, independent and identically distributed for each particle and timestep. The force from an optical trap is proportional to the displacement of the bead from that trap $x_i - x_{\mathrm{T}j}$, giving a force $-\kappa(x_i - x_{\mathrm{T}j})$, where κ is the spring constant of a trap. Finally, viscous drag gives rise to a force proportional to velocity $-\gamma\dot{x}_i$ where $\dot{x}$ represents the first derivative with respect to time and γ is the friction coefficient. These can be combined in the Langevin equation for a trapped particle $-\kappa\sum_j(x_i - x_{\mathrm{T}j}) - \gamma\dot{x}_i = \zeta$. Solving this for the motion of a particle over a time δ and explicitly showing the dependence of x_i on time, we find $x_i(t+\delta) = x_i(t) + R - \alpha\sum_j\left(x_i(t) - x_{\mathrm{T}j}(t)\right)$, where $\alpha = 1 - \exp(\kappa\delta/\gamma)$ is related to the rate at which the particle returns to the centre of the trap following a displacement and R is a Gaussian random variable representing Brownian motion. However, the linear force-displacement relationship is only valid for small displacements. We therefore introduce a cubic term such that the force falls to zero at the "capture radius" r_c (i.e. the maximum distance at which the particle experiences a force), which is around one particle diameter.

We typically measure the positions of all particles which are in (or near) optical traps with image analysis. HOTs position the traps in an extremely repeatable way, so it is not necessary to directly measure the trap positions $x_{\mathrm{T}j}$ in order to infer the forces $\kappa(x - x_{\mathrm{T}})$. At each simulation step, we add the random displacement R to each particle's position, then we add the displacement for each trap closer than r_c; $x_i = x_i - \alpha\left(x_i - x_{\mathrm{T}j}\right)\left(1 - d_{ij}^2/r_c\right)$, where d_{ij} is the 3D distance between bead i and trap j. We then add in the "scattering force" from the laser, which we approximate as an upwards force on each particle in a trap (causing particles to sit slightly above the trap positions) and also add in a small downwards force on each bead to represent gravity $z_i = z_i - v_{\mathrm{s}}\delta$ where v_{s} is set such that the particles sediment to the bottom of the simulation volume in a few seconds. Experienced users validated that interacting with the simulator was close enough to the real system.

EXPERIMENT DESIGN

To test the impact of the multimodal feedback we compared the original iTweezers application with the new application with the additional vibration and audio feedback enabled. All twelve participants were considered novice users, as they had never used optical tweezers or similar systems before. The task design for each trial involved ten particles being placed at random coordinates on the screen, as illustrated in Fig.$\tilde{1}$. Users were told to collect all the particles and deposit them in a target area, which is shown as a blue square on the interface, avoiding varying numbers of obstacles. Each trial run had a different layout and required path, but the experiment was constant across all participants. Users were split evenly into two groups, with one group performing evenly-numbered tasks with multimodal feedback and odd-numbered tasks with just visual feedback, and the other group performing the reverse. Each trial run contains specific obstacles around which the user had to navigate. If a particle comes into contact with one of these obstacles, an error is logged by the system. Likewise, if the user attempts to move a particle too quickly, and the particle is dropped, an error is logged. These reported errors, along with the overall time to complete each task, provide a performance measure of the completed task.

Early experiments with a single trap showed negligible differences between the feedback modes, due to the ease of control, so in order to challenge the users appropriately, three traps were provided to pick up the particles. This meant that the overall power of each trap was divided by a third, making it much more easy to drop a particle. This made the task of moving a particle with a trap require greater concentration. As the participants progressed through the trials, the skill required to complete them error-free increased. Each sequential task involved one additional obstacle placed at random coordinates, meaning users must deviate their path in order to avoid them while increasing the risk of causing errors. In all tasks, all finger contacts were logged. This information provides us with a descriptive metric of the user behaviour differences between the original system and the feedback enabled one. Each user performed 15 trials, but we ignored the data from the first trial for each user. Two performance metrics were used: Time to completion, t_c, Number of errors N_e. The particle trajectories were also recorded for analysis.

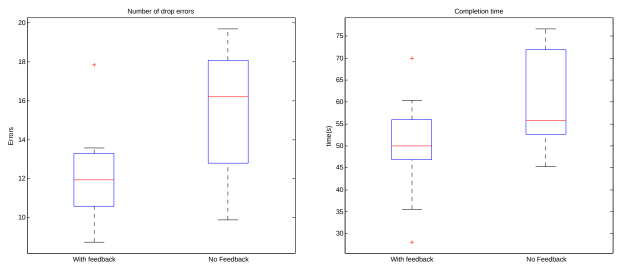

Figure 3: a) Box plots comparing error rates (N_e) and time to completion (t_c). With feedback, t_c was ($\mu = 50.01s, \sigma = 10.91$), Without feedback t_c was ($\mu = 60.04s, \sigma = 11.11$). With feedback N_e was ($\mu = 12.14, \sigma = 2.34$), Without feedback N_e was ($\mu = 15.39, \sigma = 3.45$).

A separate experiment was included to evaluate force control ability, a task with a circular obstacle around which users had to drag a bead at a constant force. This involved three expert users (physicists who were experienced in particle manipulation in microscopes using the iTweezer system, and who were generally faster and less error prone than naive users), and 12 naive users (graduate students in their 20s) who had never worked with the system, randomly allocated to multimodal or visual conditions.

RESULTS

Users with multimodal feedback performed significantly more quickly (on a Wilcoxon paired two-sided signed rank test at $p = 0.0005$), taking only 83% of the time, averaged over all three-trap trials. Despite the increased speed, users did this with significantly fewer drop errors (on a Wilcoxon paired two-sided rank test at $p = 0.0132$), an average of 3.25 fewer per trial, 78% of the error rate without feedback. The distribution of these data are summarised in Boxplots in figure 3 for the 12 naive users. The force variability experiment also showed a difference between visual and multimodal cases, where users with multimodal feedback had less variability in the distance of the trap from the bead during the circumnavigation of the circle $\sigma_f = 16.09$ compared to $\sigma_f = 26.86$, so users were better able to apply constant force on an object, while moving around the perimeter of the object's boundaries. However this result is not significant, with a $p = 0.1213$ on a Kruskal-Wallis test.

CONCLUSIONS

A combination of vibrotactile and audio feedback improved the usability of a tablet application for control of optical tweezers at the micron scale. The experiments demonstrate that the use of real-time synthesised multimodal feedback improved task performance in a touch-controlled, tablet-based optical tweezers application, significantly increasing speed and decreasing error rates in object placement tasks. In terms of subjective feedback, most users commented on the multimodal feedback making them aware of dropping the ball more rapidly without having to devote too much visual attention to each trapped object. Several said that after using the multimodal condition, they found the effort increased when they moved to visual-only. Professional users (who were not part of the experiment) were faster than naive users in all conditions, but they still commented on how surprised they were about the added value of the multimodal feedback. The fact that users have the sensation of direct physical contact with micron-sized objects which they could never normally perceive is also something that excited even professional scientists, and suggests potential applications of this in teaching and public engagement situations.

ACKNOWLEDGEMENTS

Support from the Scottish Informatics and Computing Science Alliance (SICSA), SUPA | Physics Scotland, EPSRC, Nokia and a University of Glasgow summer studentship.

REFERENCES

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(5):288–290, 1986.
2. R. W. Bowman, G. Gibson, D. Carberry, L. Picco, M. Miles, and M. J. Padgett. iTweezers: optical micromanipulation controlled by an Apple iPad. *Journal of Optics*, 13(044002), 2011.
3. S. Brewster, F. Chohan, and L. Brown. Tactile feedback for mobile interactions. In *Proc. SIGCHI*, pages 159–162, New York, NY, USA, 2007. ACM.
4. J. A. Grieve, A. Ulcinas, S. Subramanian, G. M. Gibson, M. J. Padgett, D. M. Carberry, and M. J. Miles. Hands-on with optical tweezers: a multitouch interface for holographic optical trapping. *Optics Express*, 17(5):3595–3602, 2009.
5. J. Leach, K. Wulff, G. Sinclair, P. Jordan, J. Courtial, L. Thomson, G. Gibson, K. Karunwi, J. Cooper, Z. J. Laczik, and M. Padgett. Interactive approach to optical tweezers control. *Appl. Opt.*, 45(5):897–903, 2006.
6. D. Menzies. Physical audio for virtual environments, phya in review. In *ICAD'07*, pages 197–202, 2007.
7. J. E. Molloy, J. E. Burns, J. Kendrick-jones, R. T. Tregear, and D. C. S. White. Movement and force produced by a single myosin head. *Nature*, 378(6553):209–212, 1995.
8. M. Rath. Energy-stable modelling of contacting modal objects with piece-wise linear interaction force. In *DAFx-08*, Espoo, Finland, 2008.
9. M. Reicherter, T. Haist, E. Wagemann, and H. Tiziani. Optical particle trapping with computer-generated holograms written on a liquid-crystal display. *Opt. Lett.*, 24(9):608–610, 1999.
10. K. van del Doel, P. G. Kry, and D. K. Pai. Foleyautomatic: Physically-based sound effects for interactive simulation and animation. In *Siggraph'01*, 2001.
11. D. Vogel and R. Balakrishnan. Occlusion-aware interfaces. In *SIGCHI'10*, pages 263–272. ACM, 2010.
12. J. Williamson, R. Murray-Smith, and S. Hughes. Shoogle: Multimodal excitatory interaction on mobile devices. In *CHI '07*, pages 121–124. ACM Press, 2007.