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2037-5

Introduction to Optofluidics

1 - 5 June 2009

Use of high-speed imaging technique for applications in optical tweezers

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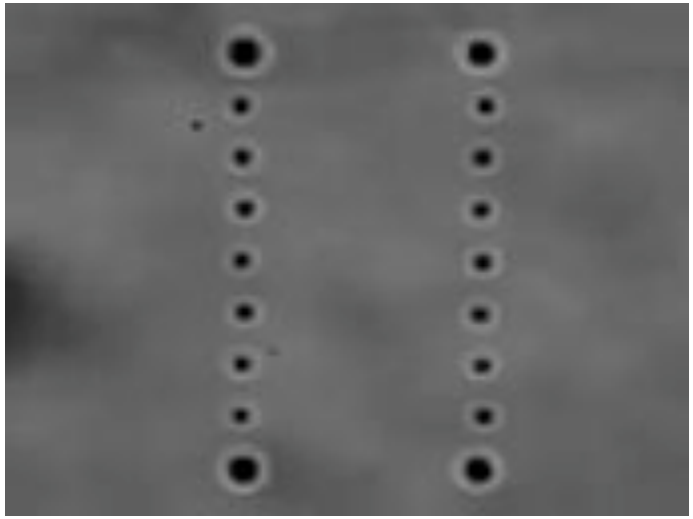
Use of high-speed imaging technique for applications in optical tweezers

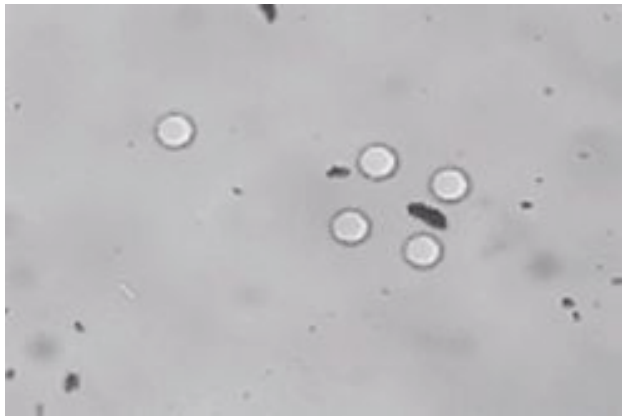
Miles Padgett

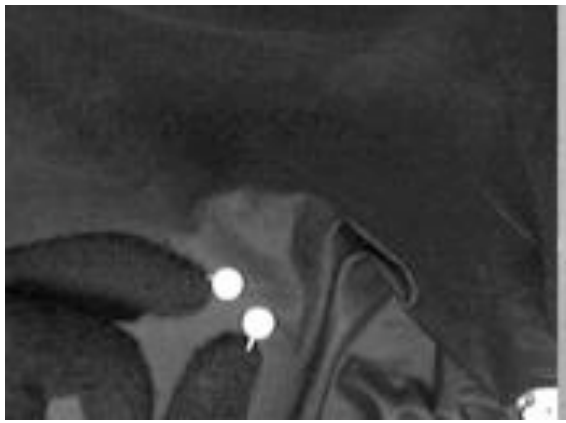
Department of Physics and Astronomy

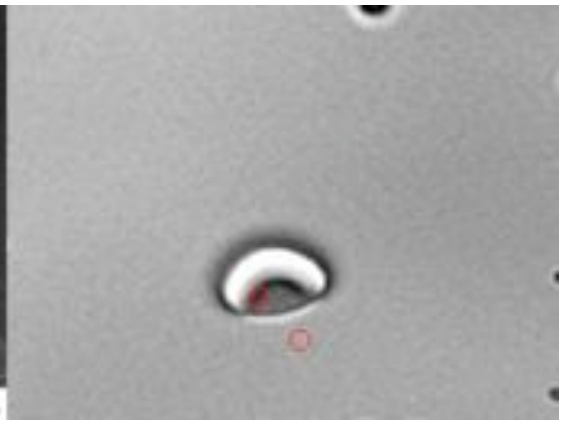
University of Glasgow

My last lecture – interfaces to holographic tweezers









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Part 2

- Methods and Applications of High-speed Imaging
  - Flow meter
  - Hydrodynamic coupling
  - Trap dynamics
  - Haptic feedback

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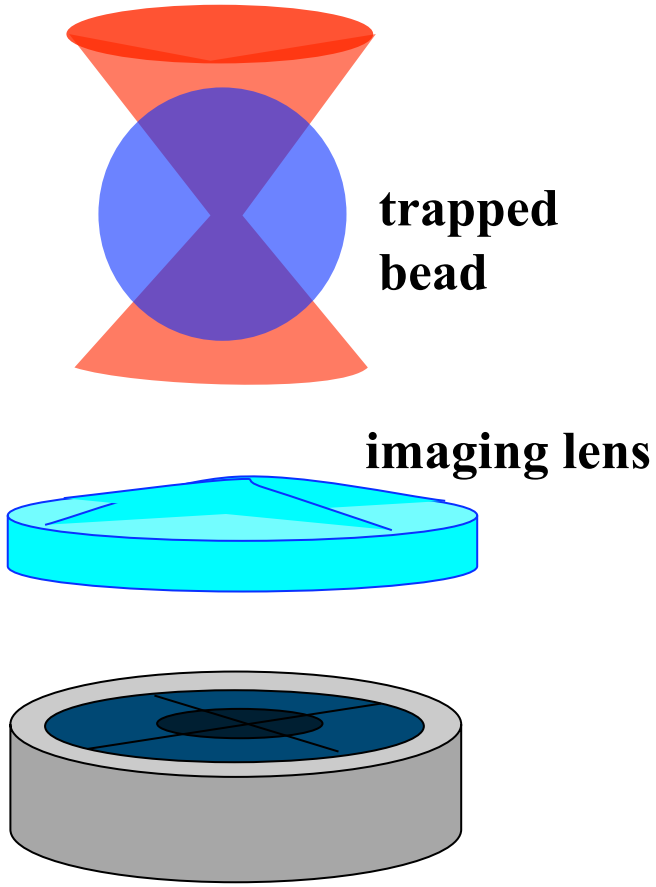
Where's that particle?

- Particles shadow on a quadrant detector
  - Differential signal from quadrants gives< nm precision!
  - >10kHz response
  - Precision limit is thermal noise in amplifiers
  - Can use deflected laser light for more signal
- Video?
  - Limited by frame rate
  - Determine (sub pixel) particle position from "centre of mass"
  - Precision/speed limit by signal



Pralle *et al*. Appl. Phys. A 66, S71, 1998

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8-bit Firewire (images buffered on camera)

- CCD (1024x1024)
- 8-bit digitisation
- Full-field frame-rate 500Hz
- Reduced frame-rate upto 16kHz
  - “letter box” R.O.I
- Images stored in camera and subsequently downloaded…..
  - 4secs of data takes ≈10mins to download

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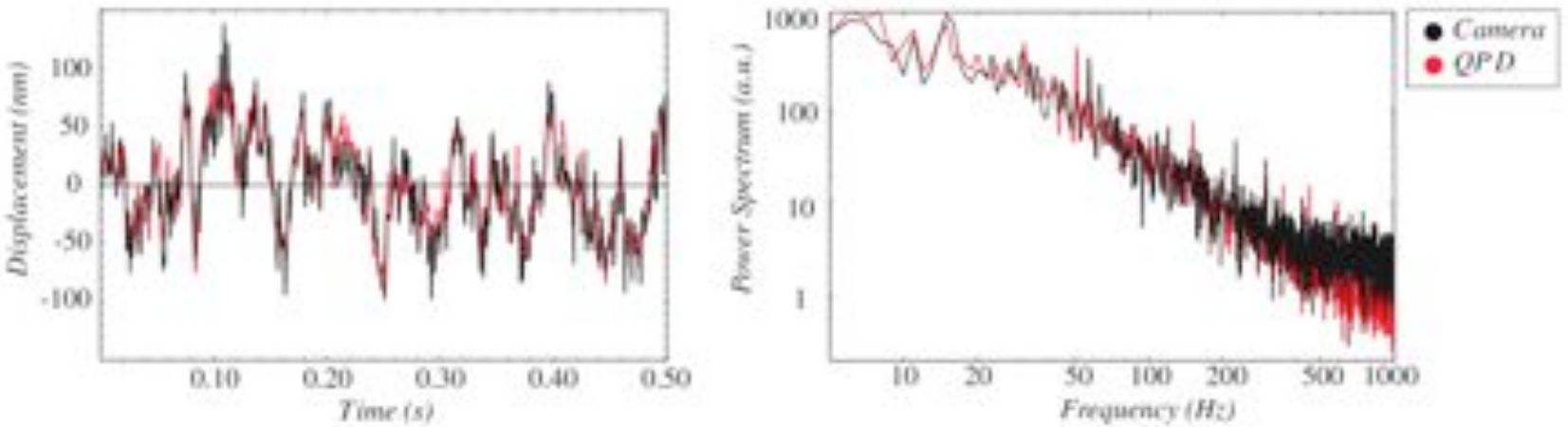
High speed video v.s. Quadrant Cell



Keen *et al*. J. Opt. A, 9, 264, 2007

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12-bit Firewire

- CCD (1392x1040)
- 12-bit digitisation
- Full-field frame-rate ≈ 20Hz
- LabView drivers
- Controlable shutter speed

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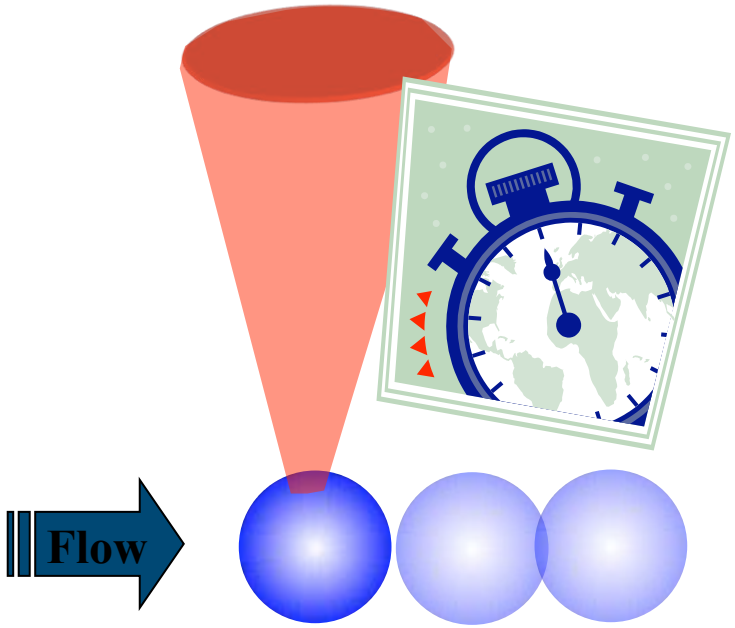
"Speed camera" for fluid flow

- Take two short exposure images with fixed time offset (10msec)
- Calibration independent of trap characteristics
- Flow rate 0.1-50μm/s
- N.B. v/(dv/dt) <1μsec



Stokes drag

$F=6\pi r\eta v$

v/(dv/dt) <1μsec

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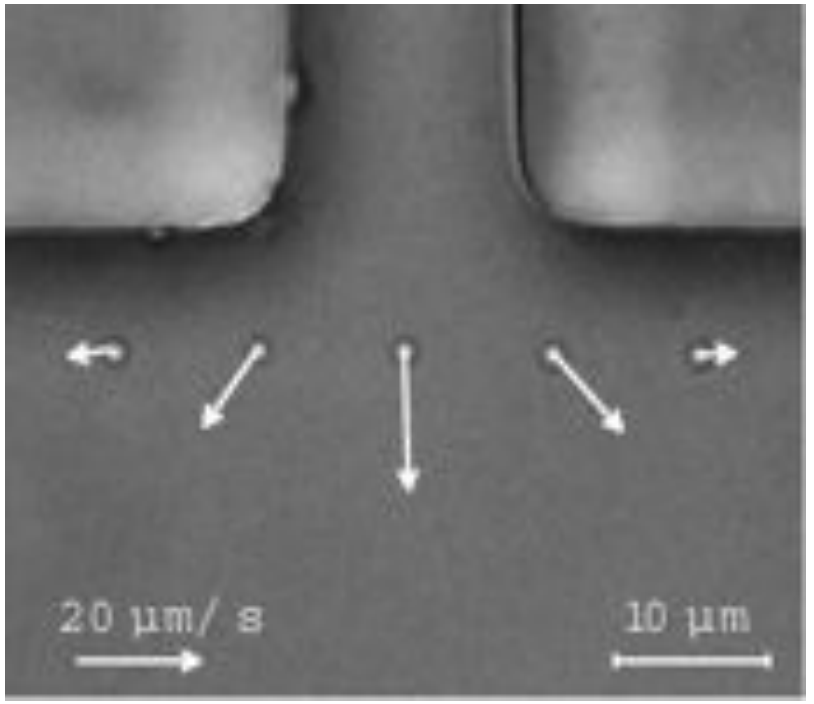
Measuring flow (2D) in micro-fluidic channel (3D)

- 15μm wide channel in PDMS
  - e-beam mask
  - Expose photo resist on silicon wafer
  - Dry etch to leave channel negative (ridges)
  - Coat with PDMS
  - Peel off to give channel network
  - Seal with cover-slip



DiLeonardo *et al.* PRL, 96, 134502, 2006

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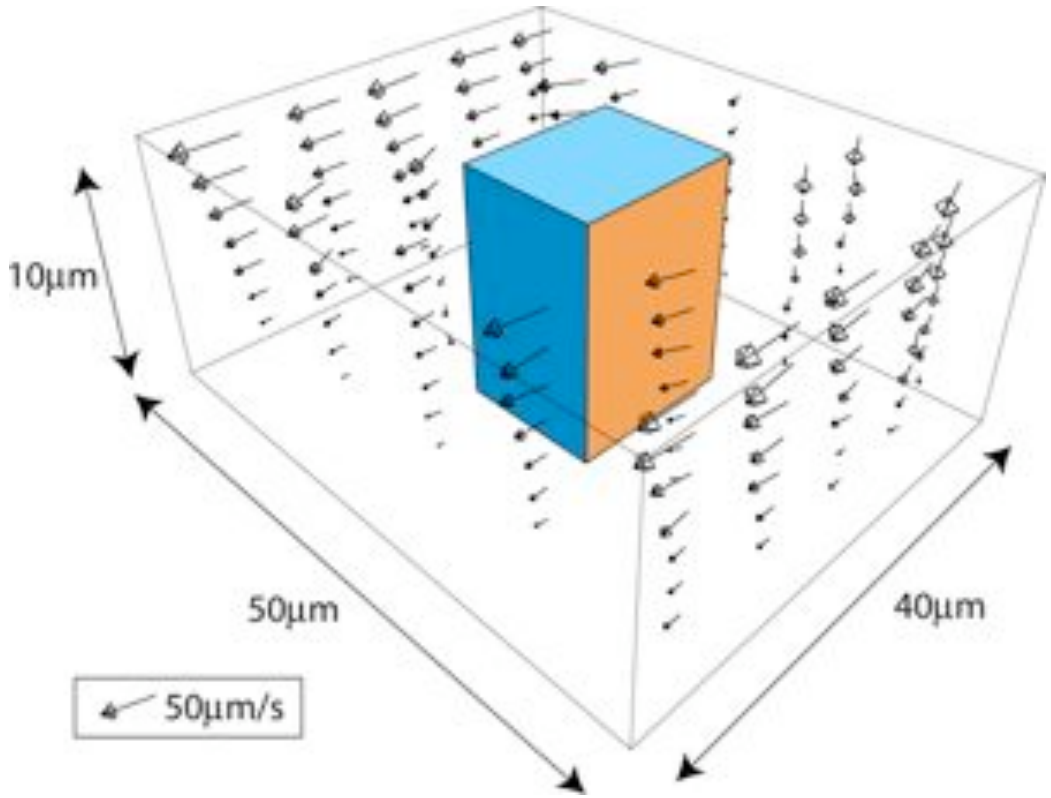
Mapping of 3D fluid Flow



Mushfique *et al.* Proc. IMechE, 222, 829, 2006

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Commercial (cheap) CMOS

- CMOS (1280x1024)
- 8-bit digitisation
- Full-field, frame rate ≈ 30Hz
- Fully selectable R.O.I (100x100).
  - Frame rate upto 1kHz
- LabView drivers
  - Can calculate centre-of-mass positions in real time

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Limits on Particle Tracking

- The Thermal Limit (?)

– What is the best (open-loop) accuracy we can get when measuring the force on a bead?

  - Brownian motion makes the particle wobble about its equilibrium position in the trap (uncertainty so uncertainty in force is approximately constant)
  - Camera noise makes the particle appear to wobble about its true position
  - We average over multiple measurements to find the equilibrium position in the trap (i.e. a force other than Brownian motion), so
    - Does higher bandwidth mean better accuracy?
  - No: measurements must be independent ⇒ Maximum useful frequency.

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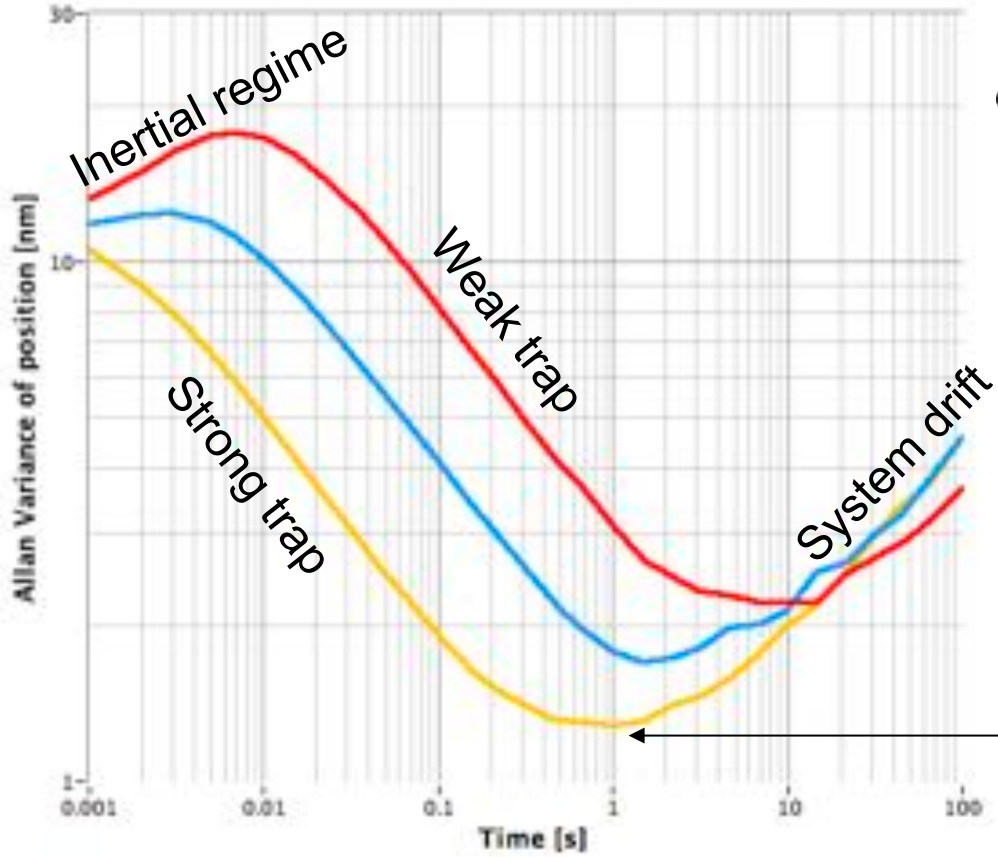
Allan Variance of particle position



$$\sigma_y(\tau) = \sqrt{\frac{1}{2}\left\langle (y_{n+1} - y_n)^2 \right\rangle}$$

≈2nm

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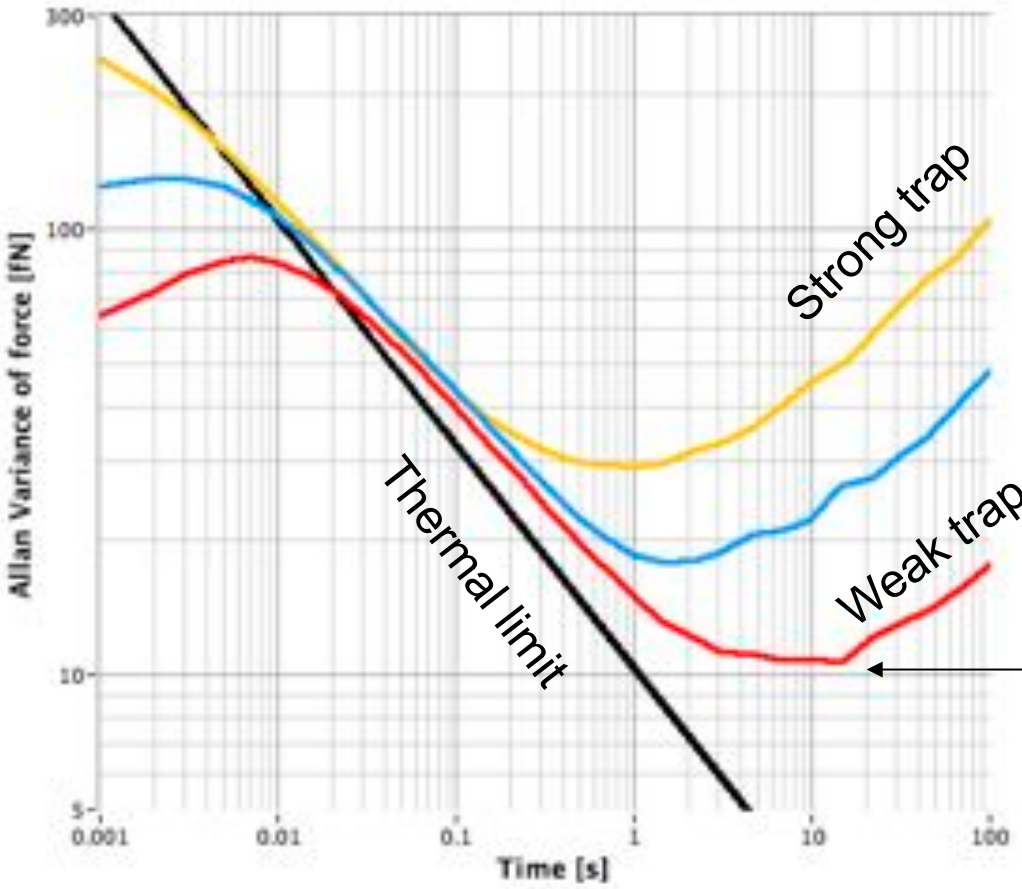
Allan Variance of (open loop) force measurement



$$\sigma_F = \sqrt{\frac{12\pi^2 \eta a k_B T \sqrt{2}}{\Delta t}}$$

≈10fN

Gibson *et al*. Opt. Exp, 14561, 2008

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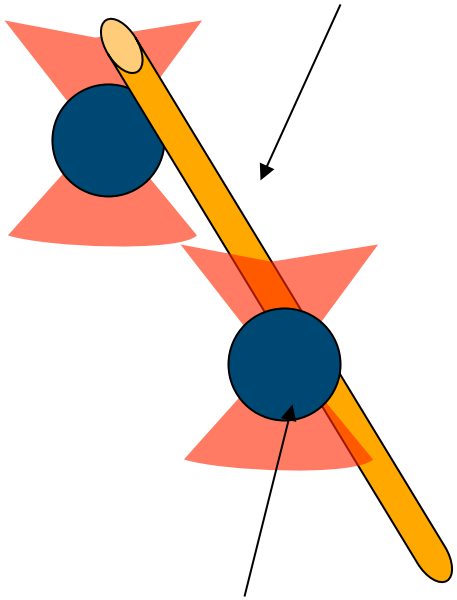
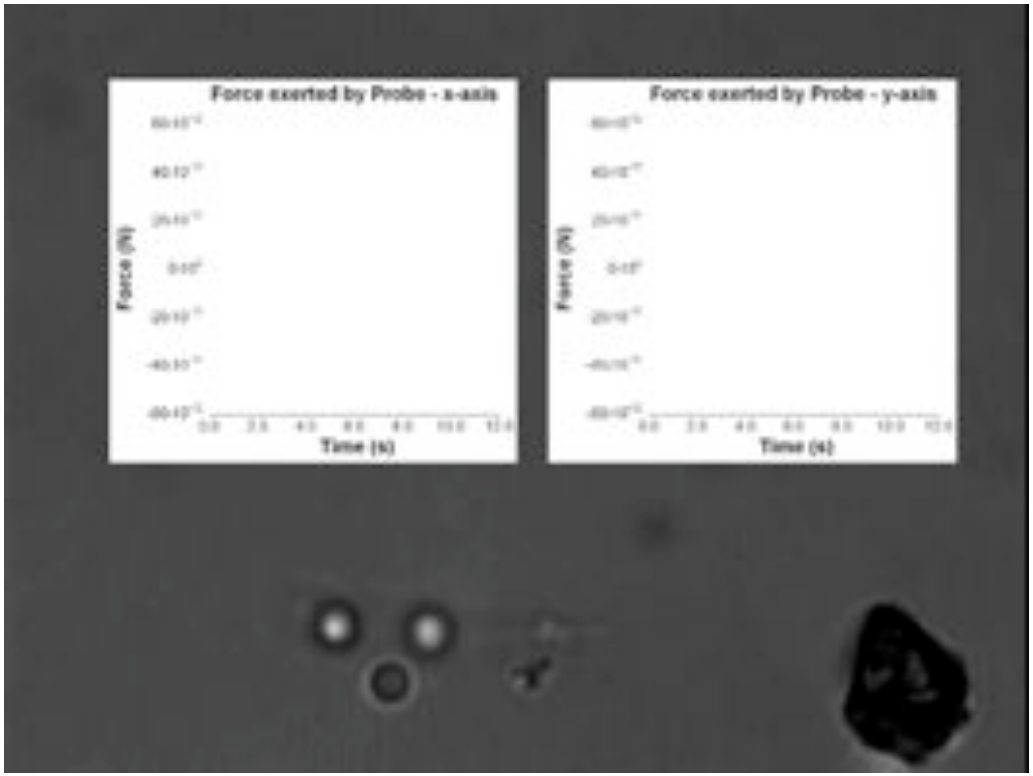
Tweezed probes (collab. Miles and Carberry Bristol)

<100nm dia. CdS (biotin)



2μm dia silica (streptavidin)

AFM nN-pN (@<nm)
Tweezers pN-fN (@>10 nm)



L. Ikin *et al.* New J Phys. 11, 023012, 2009

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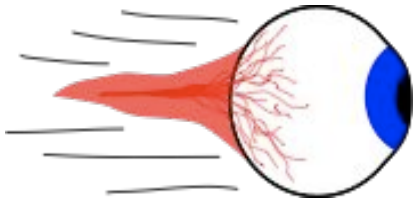
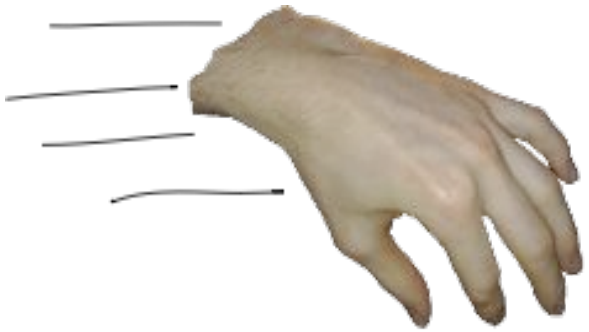
Motivation for Haptic Feedback

- The Hand is Faster than the Eye
  - We track movement visually with a bandwidth of about 24Hz



  - We sense forces with a bandwidth of about 1000Hz
    - The hand is a natural force sensor



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Haptic Feedback

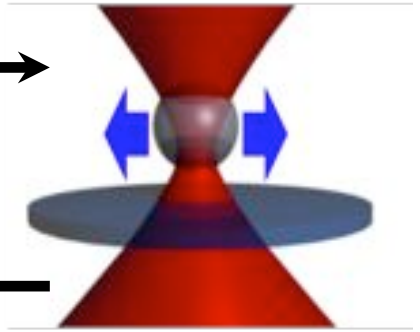
Position →

← Force

?

Position →

← Force



Macroworld
(Haptic Controller)
Novint Falcon

Microworld
(Optical
Tweezers)

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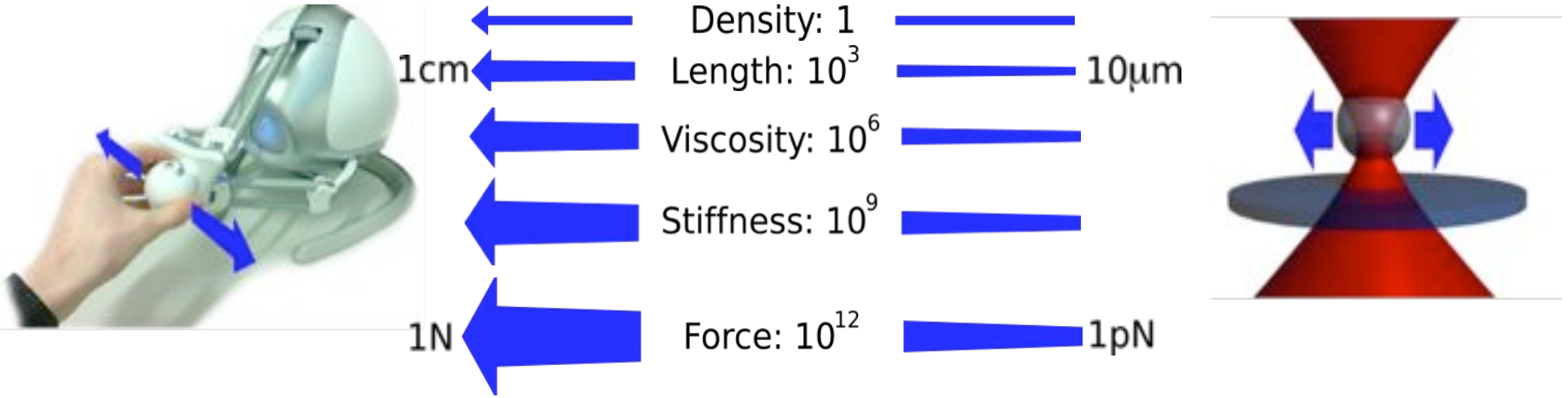
Haptic Feedback

- Coupling the Microworld to the Macroworld
  - Microworld quantities are of very different magnitudes



  - Microworld dynamics are very different
    - Microworld $F \propto \gamma \frac{\mathrm{d}x}{\mathrm{d}t} + F_{Brownian}$
    - Macroworld $F \propto m \frac{\mathrm{d}^2x}{\mathrm{d}t^2} + mg$

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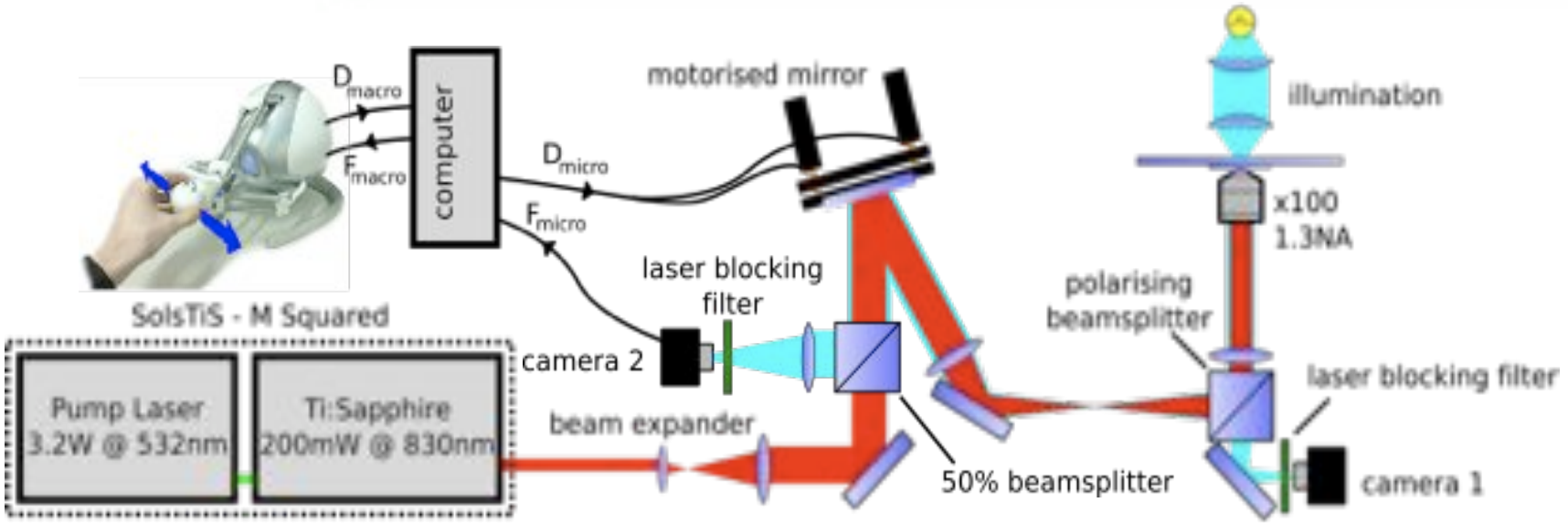
Implementing the System



- "De-Scanned" Camera for Force Measurement
  - Image moves as trap is steered
  - Image of laser spot stays fixed
  - Makes it simple to measure
    - No need to track the spot
    - Insensitive to tracking errors/lag
    - ROI on camera can be small

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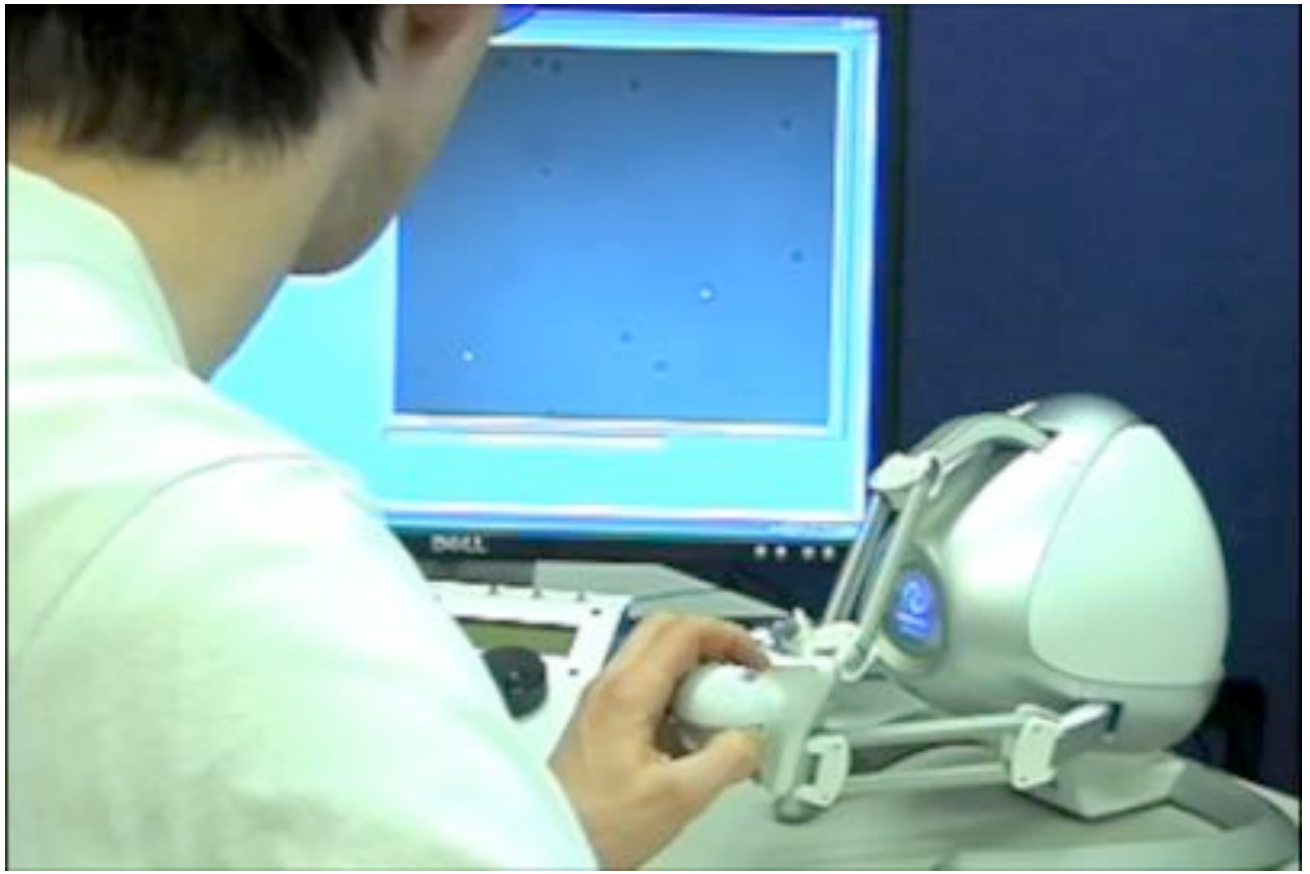
Haptic Feedback in Action



Pacoret *et al*. in press Opt. Express 2009

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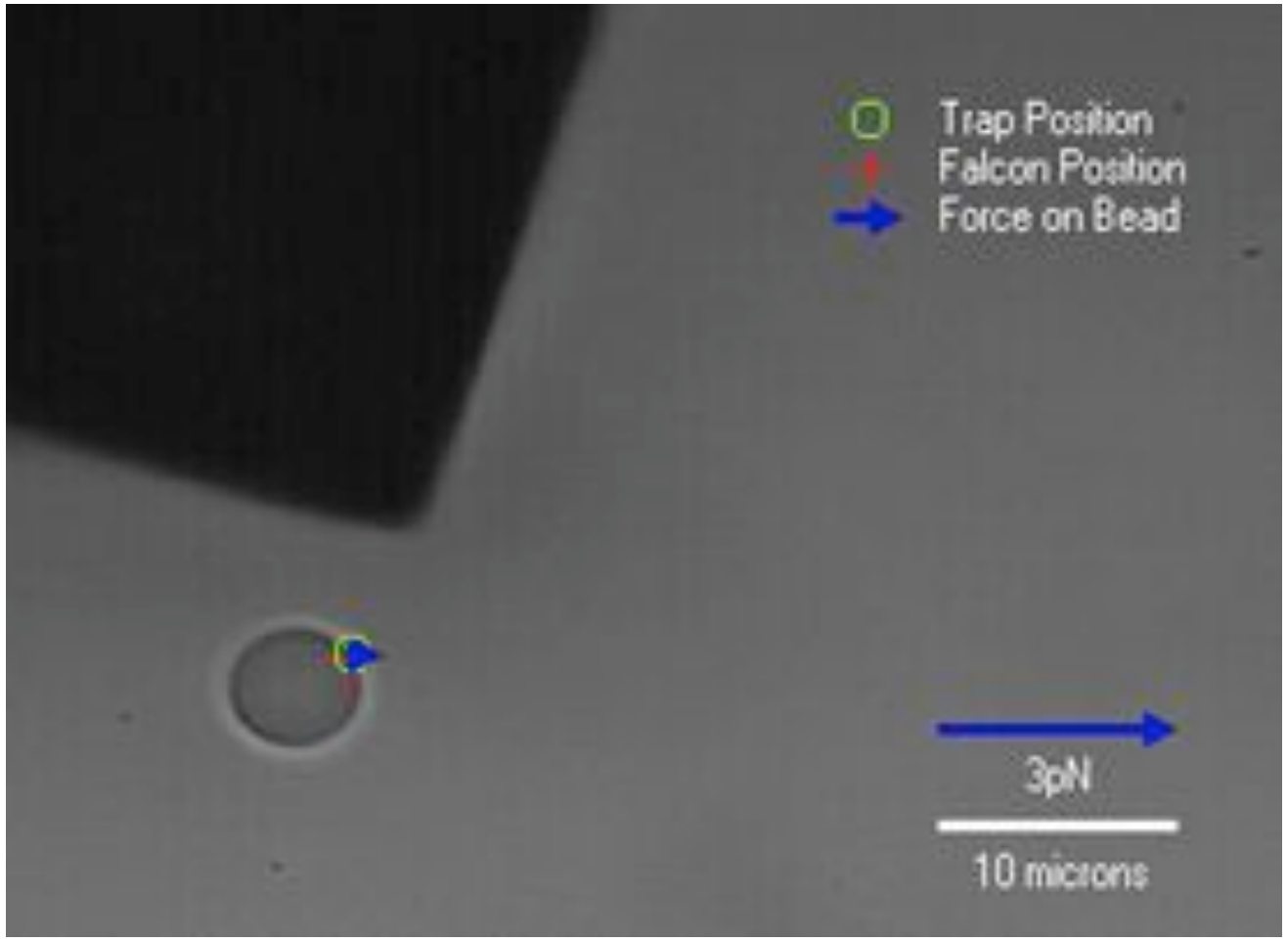
Haptic Feedback in Action



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Force Measurement

- Video Particle Tracking
  - Simple set-up
    - Calibration of pixel size can be done with a calibration slide
    - Calibrating the trap requires no assumptions about viscosity, particle size, etc.
  - Non-Spherical Particles
    - Image analysis can track more complex particles (e.g. cells)
  - Multiple Particles
    - Several particles can appear in each camera frame
    - Compatible with e.g. holographic techniques
  - High Speed
    - Image acquisition faster than 1kHz (with modern CMOS cameras)
    - Processing on-the-fly using a centre-of-mass algorithm on a standard PC

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Cameras for Particle Tracking

- High Speed Cameras
  - Buffer-based devices
    - Store images in a buffer at high-speed
    - Download images later and analyse offline
    - Limited recording length, not real-time
  - Smart Cameras
    - Hardware image analysis, send only coordinates of particles
    - Best bandwidth (several kHz)
    - Measure up to 16 particles
  - CMOS Cameras
    - Reduced region of interest (ROI) to save bandwi
    - Cheap and flexible
    - Image analysis of multiple particles on a desktop

Redlake Digital Imaging Systems
http://www.redlake.com

Durham Smart Imaging
http://www.durhamsi.co.uk

Prosilica EC1280
http://www.prosilica.com