Micro Manipulation for Precision Manufacturing and Biomedical Applications

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New Zealand is located in the South Pacific between the Pacific Ocean and the Tasman Sea, between latitude 35 and 45 degrees south.
Liveable Place

- In 1996, Christchurch was acknowledged as the outstanding garden city from 620 international entries.
- In 1997, Christchurch was judged Overall Winner of Major Cities in the Nations in Bloom International Competition to become 'Garden City of the World'!

“I think every person..... dreams of finding some enchanted place of beautiful mountains and breathtaking coastlines, clear lakes and amazing wildlife. Most people give up on it because they never get to New Zealand”

Mr. Bill Clinton – Former US President
Gala Dinner, Christchurch, NZ 2000
Agenda

- Overview of Mechatronics@UC
- Precision Assembly For Optical MEMS Switch Packaging
- Microrobotic Cell Injection
- Force Pattern Characterization of C. elegans
- Conclusions
Who are involved

- **Supervising Team:**
  - Assoc Prof XiaoQi Chen (Director for Mechatronics) - robotics, mechatronic systems
  - Prof J Geoff Chase - dynamics and control, bioengineering, structural
  - Dr Wenhui Wang - robotics, bio-mechatronics
  - Dr Stefanie Gutschmidt - dynamics and vibration
  - Dept of Electrical Engineering, Computer Science, MacDiarmid, HITLab, Bioengineering Centre

- **Technical Support**
  - Mechatronics and electronics technicians: Rodney Elliot, Julian Murphy, Julian Philips,
  - Mechanical workshop

- **Postgraduates**
  - James Pinchin, PhD - Low-cost GPS based attitude solution using multiple software based receivers.
  - Patrick Wolm, MEng – Dynamic stability control of front wheel drive wheelchairs.
  - Scott Green, PhD - Human Robot Collaboration Utilising Augmented Reality
  - Ali Ghanbari, PhD – MEMS actuation and precision micromanipulation.
  - Mostafa Nayyerloo, PhD, – Structural health monitoring
  - Chris Hardie, MEng – biologically inspired robots
  - Matthew Keir, PhD – Head motion tracking, graduated in 2008

- **Visiting Researchers / Fellows**
  - Prof Richard King, Oregon Institute of Technology, Jun 2006 – Mar 2007
  - Prof Clarence de Silva, University of British Colombia, 1-31 August 2008
  - Australian DEST Endeavour Fellowship, Mr Ben Horan, Aug – Dec 2008. Haptics technology

- **Interns**
  - Julien Dufeu, Institut Francais de Mecanique Avancée (IFMA), 2007. Modelling of wall climbing device
  - Matthias Wagner, the University of Munich, 2007. Design of wall climbing robot.
  - Harald Zophoniasson, ENISE, France, 2008. High-precision motorised stage

- **Industrial Collaborators**
  - Geospatial Research Centre, Dynamic Controls Limited, Industrial Research Limited (IRL), Commtest, etc.
**Mechatronics@UC**

**Bio-mechatronics**
- Assistive devices for rehabilitation
- Bio-micromanipulation – cell injection

**Mobile Robotics**
- Unmanned aerial vehicle, micro air vehicle
- Underwater vehicle for bio-security inspection
- Wall-climb robot for tank welding

**Instrumentation and Automation**
- Manufacturing
- Structural control
- Energy harvesting
- Bio-scaffolding
Digital Image-Based Elasto-Tomography

The DIET system is broken down into 4 fundamental steps: (1) Actuation → (2) Image Capture → (3) Motion Tracking and measurement → (4) Tissue stiffness reconstruction

1. A woman’s breast is vibrated by an actuator and imaged with high-resolution digital cameras.

2. Spatially calibrated digital cameras combined with a motion sensor measures the surface motion of the breast.

3. Finite Element method converts the measured breast surface motion into a 3-D stiffness distribution, where regions of high stiffness suggest cancer.
Variable Resistance Rehabilitation Device

Provisional Patent (2008)
UC Wall-Climbing Robot - Performance

- Total weight: 234g
- Max attraction force (at 5 bar): 12N

The robot is able to transverse the gaps on the wall.

High manoeuvrability in every direction, and on different surfaces.

Video: Climbing different surfaces and ceiling

Additional weight that can be lifted (on a wall as on a ceiling): 500g

Provisional Patent (2008)

FDM Validation with On-Board Instruments

- Equipment used
  - 2.4 meter wing-span gas powered RC plane
  - GPS base station
  - Inertia navigation system
  - Servo pulse acquisition device
  - Wind speed sensor
  - Data logger
  - Wind tunnel

Canterbury UUV - Biosecurity

For shallow waters, up to 20m depth

Flexure-Based Precision Assembly of Optical MEMS Switch Packaging
Background

- State of the art: automated micro-assembly

  - **Active micro-assembly (sensor-based)**
    - Servoing with force sensors
      (ESEC, Switzerland; Klocke Nanotecknik, Germany)
    - Servoing with vision image
      (Universal, USA; Sandia, USA)

  - **Passive micro-assembly (task-based)**
    - Positioning fibers by V-grooves
      (Suss MicroTec, USA, Lucent, USA)
    - Positioning micro chips by silicon optical benches
      (Sysmelec, Switzerland; AXSUN, USA)
Background

Objective of Research

To develop a low-cost, robust and efficient method for those micro assembly tasks needing insertion operation.

• Test-bed:

Assembly of optical MEME switches

An optical switch with one input channel and four output channels, developed by SIMTech

Desired assembly configuration
Assembly Process Analysis

➢ Assembly Uncertainties

Four kinds of assembly errors

✓ Lateral offset
✓ Yaw angle offset
✓ Tilt angle offset (studied in future work)
✓ Axis offset (don’t affect mating, but affect light coupling)

Fiber insertion operation
Assembly process analysis

Without fiber slip or rotation during insertion

Threshold curve of contact force for secure grip of fiber

Quasi-kinematics model of contact

\( F_a \): contact force
\( F_v \): vacuum force
\( \mu_1 \) and \( \mu_2 \): coefficients of friction of point A and C
\( \phi \): half angle of vacuum head
Assembly process analysis

- **Component protection**

- Contact forces have to be less than the threshold

Threshold curve of contact force for component safety

Component damage simulation by ANSYS
Assembly process analysis

- **Successful insertion condition:**
  - Without losing-grip
  - Without component damage

Environment compliance have a significant effect on performance in terms of contact force and grip.
Assembly process analysis

Requirements of Assembly

• Max allowable angular error $\alpha_{\text{max}} = 0.05 \text{ deg}$, and lateral error $e_{\text{max}} = 10 \text{ um}$,

(the accuracy that normal precision PnP can reach)

• Isotropic translational compliance in all direction

  $k_{\text{LX}} = k_{\text{LY}} = 26 \text{ mN/um}$

• Required angular compliance

  $k_T = 11\text{Nmm/deg}$
Flexure-based Fixture Design

➢ Flexure-Based Mechanisms

Flexures are compliant joints that provide motion by material deformation within elastic range

- No backlash and clearance
- Not need assembly
- Compact size
- Can be designed based on stiffness

Joints’ $K_q$, $K_p$ ➔ Flexure design ➔ Flexure type and size

An example conversing normal joint to flexure
Flexure-based Fixture Design

- A flexure-based fixture for MEMS assembly

Compliance

\[ K_x = K_y = 26 \text{ mN/um} \]

\[ K_\theta = 11 \text{ Nmm/deg} \]

\[ x, y, \theta \]

Flexure design

Topological synthesis

\[ k_x = \frac{3}{2} \left( k_q + \frac{1}{q} k_\phi + \frac{1}{q} k_\psi \right) \]

\[ k_y = k_x \]

\[ k_\theta = 3k_q b^2 \cos^2(\phi + \theta) + \frac{3k_\phi}{q^2} b^2 \sin^2(\phi + \theta) + \frac{3k_\psi}{q^2} (b \sin(\phi + \theta) + q)^2 \]

Configuration optimization

\[ k_x = \frac{3}{2} \left( k_q + \frac{1}{q} k_\phi + \frac{1}{q} k_\psi \right) \]

\[ k_y = k_x \]

\[ k_\theta = \frac{3k_\phi}{q^2} b^2 + \frac{3k_\psi}{q^2} (b + q)^2 \]
Experiment Results

➤ Experiment Setup

Vacuum head: V-shaped head, providing 25.6 mN suction force to the fiber

Floating fixture: flexure-based mechanism, providing required compliance in x-y-θ axes

Force sensor: monitor the insertion force

Monitoring camera: monitor the insertion errors

6-axes stage: set the required initial errors for test

A flexure-based passive micro assembly system
Results and Analysis

Comparison of the maximum contact forces

Fiber insert into U-groove without help of the floating fixture

Fiber insert into U-groove successfully with help of the floating fixture

Comparison of the maximum contact forces

- Theoretical results with floating fixture
- Experiment results with floating fixture
- Theoretical results without floating fixture
- Experiment results without floating fixture
Microrobotic Cell Injection

- Cell Patterning
- Determine 3D information from 2D imaging
- Cell Injection

Challenges to Tackle

- Immobilize a large number of cells into a regular pattern
- 3D manipulation with 2D microscopy visual feedback
- Robust image processing
- Coordinately control two microrobots
- Optimization of operation parameters to minimize lysis
Embryo Holding Device
Detailed structure

(a) cell (e.g., zebrafish embryo) micropipette reservoir to vacuum pump step

(b) through-hole slope outlet step

(c) airflow channels
Sample Preparation
Contact Detection

Where is the surface?

Can we get 3D (Z) information from 2D (image plane x-y) information?
Contact Detection Principle

contact detection procedure animation

Recognition of Embryo Structures

- Adaptive thresholding and morphological operations
- Snake tracking and convex deficiency calculations
- Recognition of chorion, cell, yolk, and cytoplasm center
Coordinate Frames & Transformation

\[ e R_c = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \]

\[ t R_c = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \]

\[ s = \begin{bmatrix} s_x & 0 \\ 0 & s_y \end{bmatrix} \]

\[ s \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} X \\ Y \end{bmatrix} \]

\[ s^i p = ^c P \quad (1) \]

microrobotic frames vs. camera frame

microrobotic frames vs. image frame

\[ ^e P = ^e R_c \cdot ^c P + ^e t_c \]

\[ ^t P = ^t R_c \cdot ^c P + ^t t_c \]

\[ ^e P = ^e R_c s^i p + ^e t_c \]

\[ ^t P = ^t R_c s^i p + ^t t_c \]

tip home position

initial cytoplasm centroid
Looking-then-Moving

- Looking in image for initial positions of:
  - the tip
  - the deposition point
- Where to move in microrobotic frames?
  - coordinate frame transformation
- How to move?
  - position feedback from microrobots only

![Diagram showing a PID control system with input $P_d$, error $P_e$, and feedback $P_f$.]
Injection Control Sequence

contact detection -> batch injection
Force Pattern Characterization of \textit{C. elegans} in Motion

- Introduction to \textit{C. elegans}
- N Force Measurement Principle
- MEMS Fabrication Process
- Image Processing Algorithm
- Results

Image Source: PLoS Biol

C. elegans – Locomotion

*C(aenorhabditis) elegans*
- free-living nematode (roundworm)
- about 1 mm in length, 100µm in width
- lives in temperate soil environments
- used extensively as a model organism

*C. elegans* was the first multicellular organism to have its genome completely sequenced (1998)

**Challenging because:**
- *C. Elegans* are very small:
  - cannot use conventional force measurement techniques
- *C. Elegans* are living organisms:
  - non-intrusive measurement technique required
Cellular Force Modelling

• At force point: Bending + Shear

\[ \delta = \left( \frac{l^3}{3EI} + \frac{20(1+\nu)l}{9AE} \right) \cdot f \]

• From force point to the free end of the pillar: Just Bending

\[ \delta' = \frac{l^2}{2EI} (h - l) \cdot f \]

\[ \Delta = \delta + \delta' \]

I: moment of inertia
E: Young’s modulus
\nu: Poisson’s ratio
Detecting Pillar Deflection

Parameters for Pillar Array:
- stiffness of silicone
- pillar diameter
- spacing
- height

Image capture and processing setup
MEMS Fabrication

Spin SU-8 2025 photoresist

Expose spacer layer

Spin SU-8 2100 photoresist

Expose pillar layer

Develop and silanize

Cast and cure PDMS

Remove from mold and cover

UC Nanofabrication Laboratory
Device Molds

Ø60um

Ø80um

100um

300um
Image processing

- Without loss of generality, three specific pillars targeted for image processing
- Frames converted to black and white to have binary images
- Three zones defined to extract each pillar image in an assigned square window
- A Boundary Tracing Algorithm developed and adapted to trace the outline of the outer circle of the deflected pillars
Image processing Algorithm

- Scanning the square window from bottom left: P₀
- Searching the 3×3 neighborhood of the current pixel in an anti-clockwise direction.
- The circle point tracing is repeated up to detecting nth pixel Pₙ.
Image processing Algorithm

- A least-square fitting algorithm was employed to fit a circle to the traced points.
### MAX FORCE

<table>
<thead>
<tr>
<th></th>
<th>PILLAR 1</th>
<th>PILLAR 2</th>
<th>PILLAR 3</th>
</tr>
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<tr>
<td>$</td>
<td>f_x</td>
<td>(\mu N)$</td>
<td>17.93</td>
</tr>
<tr>
<td>$</td>
<td>f_y</td>
<td>(\mu N)$</td>
<td>6.58</td>
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<tr>
<td>$</td>
<td>f</td>
<td>(\mu N)$</td>
<td>18.15</td>
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</tbody>
</table>
Cumulative Distribution of Calculated Forces

- Sorting the all calculated forces of three pillars except zero ones from smallest to largest and distributing them between 0 to 1 with steps of one over the number of sorted forces.
- A nearly linear cumulative distribution function (CDF) will be obtained, which implies an approximately uniform distribution of forces.
- It shows a highly variable and continuous force level produced by the worm, which is in accordance with biological results and the anatomy of C. elegans.
Conclusion & Future Work

• Assistive robotic devices
  ➢ Prosthetics, Rehabilitation
  ➢ Active assistant
• Biologically inspired robots
  ➢ Biomimetics study
  ➢ Novel micro actuator and mobility control
  ➢ Situational awareness (feeler, vision, tactile, sound)
• Human machine interface technology
  ➢ Augmented reality
  ➢ Haptics device for virtual presence and virtual training
  ➢ Brain-computer interface
• Mobile robotics
  ➢ Mobility: hybrid wall climbing mechanism (Bernoulli pad++), untethered
  ➢ Sensing: vision for motion sensing in place of expensive IMU
  ➢ Environmental / resource measurement, monitoring
  ➢ Automating complex tasks in natural environment.
• Energy harvesting
  ➢ Convert mechanical energy to electric power. Cost & efficiency.
  ➢ Self-powered wireless instrument
Biomechatronics
Questions ?