Advancing Mechatronics Technologies for Bio-Instrumentation and Control

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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

- Who are involved?
- Overview of Mechatronics@UC
- Wall Climbing Robot using Non-Contact Adhesion
- 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 Avancee (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

Burwood Academy of Independent Living

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

Industrial Research Limited

NIWA Taihoronui

HITLab NZ

Geospatial Research Centre
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)
Integrated Flight Dynamics Model

- The input of aircraft geometry instead of aerodynamic coefficients greatly simplified aircraft model development
  - No wind tunnel testing is required
  - Effects on changing aircraft geometry can be seen immediately
  - Much better repeatability

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

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Canterbury UUV - Biosecurity

For shallow waters, up to 20m depth

Vehicle design and electronics

Video: QEII Pool Test

- IMU
- Pressure sensor-depth
- Webcam
- Temperature sensor
- RoboteQ motor controller
- Sliding mechanism
- Mother board
- Power supply
- Cable and canister seals
A Novel Wall Climbing Robot using Non-Contact Adhesion

Robotic research at the University of Canterbury has climbed new heights with the development of a wall-climbing robot.

The robot has been developed by a team of researchers lead by Associate Professor XiaoQi Chen in the University’s Mechanical Engineering department.

• Motivation
• The Bernoulli Effect
• Design Considerations
• Performance

**Motivation**

<table>
<thead>
<tr>
<th>Adhesion</th>
<th>Surface Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic</td>
<td>Ferromagnetic</td>
</tr>
<tr>
<td>Vacuum</td>
<td>Smooth, Non-permeable</td>
</tr>
<tr>
<td>Microfibre</td>
<td>Clean</td>
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</tbody>
</table>

Adhesion effect independent of materials and surface conditions is desirable.
Challenge

Develop a Wall Climbing robot insensible to surface conditions
Adhesion device using air pressure to create attraction force
The Bernoulli Effect

Assumptions to simplify equations:
Laminar, steady, frictionless flow, viscous effects are neglected, incompressible fluid, only forces acting are pressure and weight

\[ \frac{v^2}{2} + \frac{p}{\rho} + gh = \text{const} \]

**Bernoulli equation:**

\[ \frac{v_1^2}{2} + \frac{p_1}{\rho} + gh_1 = \frac{v_2^2}{2} + \frac{p_2}{\rho} + gh_2 \]

**The Bernoulli Effect** (Bernoulli’s Principle):

\[ \rho \frac{v^2}{2} + p = \text{const} \]

The pressure decreases with a simultaneously increasing velocity
Design Considerations

Existing Devices

- Very small attraction force

NCT device

- Heavy
- High flow rate

More efficient lightweight device is needed
The Final Bernoulli Pad

Material: Aluminium
Number of parts: 2
Undercut: 0.5mm
Nozzle gap: 0.10mm
Diameter: 45mm
Height: 18mm
Total weight: 19g
Attraction forces for different surfaces

Pressure / bar

Force / N

Glass
Polyethylene board (plastic)
Flake board (wood)
Corrugated board
Styrofoam
Rough wood
Cloth
Air cushion foil
Foam plastic
Sandpaper S600
Sandpaper S240
Sandpaper S40
Illustration of passing a 10mm gap

- Edge radius
- Ramp for undercut
- Pin

10 mm gap

Distance / mm

Force / N

4
4.5
5
5.5
6
6.5

-40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50
The Prototype Robot

Parts:

1. Plastic as main body
2. Bernoulli Pads
1. Aluminium suspension beam
2. Servo drive trains
2. Aluminium wheels with high friction tires (friction coefficient 0.74 on glass)
UC Wall-Climbing Robot - Performance

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

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

High manoeuvrability in every direction, and on different surfaces.

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

Video: Climbing different surfaces and ceiling
Microrobotic Cell Injection

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

Microrobotic Cell Injection System
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
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

\[ e \mathbf{R}_c = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \]
\[ t \mathbf{R}_c = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \]

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

\[ \mathbf{s} \mathbf{p} = \mathbf{c} \mathbf{P} \]

microrobotic frames vs. camera frame

\[ e \mathbf{P} = e \mathbf{R}_c c \mathbf{P} + e t_c \]
\[ t \mathbf{P} = t \mathbf{R}_c c \mathbf{P} + t t_c \]

microrobotic frames vs. image frame

\[ e \mathbf{P} = e \mathbf{R}_c s \mathbf{p} + e t_c \]
\[ t \mathbf{P} = t \mathbf{R}_c s \mathbf{p} + t t_c \]

view point

\[ \mathbf{s} \]

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

\[ \mathbf{u} \]

\[ \mathbf{v} \]

\[ \mathbf{p} = (u,v) \]

\[ \mathbf{p} \]

\[ \mathbf{P} = (X,Y,Z) \]

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](attachment:image.png)
Injection Control Sequence

contact detection → batch injection
Force Pattern Characterization of C. elegans in Motion

- Introduction to 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

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

\( I \): moment of inertia  
\( E \): Young’s modulus  
\( Y \): 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
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 $3 \times 3$ neighborhood of the current pixel in an anti-clockwise direction.
- The circle point tracing is repeated up to detecting $n$th pixel $P_n$.
A least-square fitting algorithm was employed to fit a circle to the traced points.
<table>
<thead>
<tr>
<th></th>
<th>PILLAR 1</th>
<th>PILLAR 2</th>
<th>PILLAR 3</th>
</tr>
</thead>
<tbody>
<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>
</tr>
<tr>
<td>$</td>
<td>f</td>
<td>(\mu N)$</td>
<td>18.15</td>
</tr>
</tbody>
</table>

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**Pillar 1**

![Graph](image1.png)

**Pillar 2**

![Graph](image2.png)

**Pillar 3**

![Graph](image3.png)
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

microsystems

Sensors

computer vision

biology

bio-medical

microbiology
Questions ?