Advanced 1
Introduction
Applications and Examples of Micro-Nano Mechatronics

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Technologies for Micro-Nano echatronics

Micro-Nano fabrication
- MEMS
- NEMS
- Machining
- Assembly
- Optics/Imaging

Robot technology
- Sensors
- Actuators
- Control theory
- Dynamics

Micro-Nano Mechatronics

Micro-Nano Materials
- Tribology
- Energy
- Synthesis
Application Fields of Micro-Nano Mechatronics

Medical field
- Surgical devices
- Endoscopic devices
- Training
- Diagnosis devices
- Implantation devices
- Welfare

Industrial field
- Micro size sensors
- Hi-sensitive sensors
- Integrated packaging
- Wireless technology
- Cost reduction
- New energy

Bio field
- Single cell sensing
- Drug delivery
- Genome analysis
- Biofuel
- Cell assembly
- Tissue engineering

Fundamental research field
- New technology establishing
- New material
- New observation

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Application Examples
- Medical Field -
Background

ESD (Endoscopic Sub-mucosal Dissection)

Excision procedure

Cancer
Marking
Cutting

Advantages
- Minimally invasive procedure
- Quick recovery

Problems
- Time-consuming
- Skill-dependent
Rerated Works

Clinical Field

Ikuta et al. (2000)
5DOF 3.0mm

Fujie et al. (2005)
3DOF 2.4mm

Olympus Medical
EndoSAMURAI

Nokata et al. (2010)
3DOF 1.4mm

Reserach Field

S–O clip, Sakamoto et al. (2008)

10mm

10mm
Decoupling Wire Driven Microarm

Design of 2DOF microarm (less than 3mm)

Channel (φ3 mm)

Wire-electric discharge  Photolithography

Ref.) Kawahara et al., Biorob, 2010
To achieve the wire decoupling, this wire for gripper is precisely passed through the center position of the arm joint.
Joint Design

- Wire decoupling
- Large movable angle

Required accuracy: 50 μm

Wire-electric discharge machining

Trapezoid frame

\[ l_1 = 0.67 \text{ mm} \]
\[ l_2 = 0.00 \text{ mm} \]
\[ \phi = 12.0 \text{ deg.} \]
Gripper Design

Pillar buckling

Muramatsu et al. (2000)

Without large mechanical elements

Normally-open type Gripper
Fabrication Process

Wire-electric discharge (Phosphor bronze: thickness 1 mm)
Fabrication Process

Photolithography + Electroplating

(Sacrificial layer)
(Nickel: thickness 0.1 mm)

Gripper Fore link Arm Joint Base link

Si
1. Spin coat LOR 5B
2. Sputter deposition [Cr, Au]
3. Photolithography

Au/Cr

KMPS 3035

Ni
4. Electroplating
5. Lift-off
6. Ultrasonic cleaning

30 mm
Fabrication Process

Gripper  Fore link  Arm Joint  Base link

Photolithography + Electroplating

**STAMP** [Arai et al. JRM, 2009]
(Stacking Microassembly Process)

Ni layer

Pin

4 layers

10 mm

1.9 mm
Animal Experiment

Conventional oral-endoscope

Channel: 2.7 mm

Pig stomach
Application Examples
- Industrial Field -
**Background**

Needs a load sensor for robotics and healthcare field.

- **Tank (20 L):** 80 kPa
- **Weight:** 20 kPa
- **¥1 coin:** 86.5 Pa

High sensitivity load sensing with a condition that compression force acted.

Expected characteristics:
1. Wide range measurement
2. Measuring a tiny variation with initial load

⇒ New principal, New type load sensor
Comparison of Conventional Load Sensors

Load Sensor Elements

- Strain Gauge
- Compressive Conductive Rubber
- Vision Sensor
- Piezoelectric Element
- Quartz Crystal

For wide range measurement, we selected Quartz Crystal.

Quartz Crystal type force sensor

- Sensing depends on the stress of the element.
- Robust against time and temperature change...
  - High sensitivity & wide range measurement
  - Excellent stability
- High frequency characteristic … High-speed measurement
- Self-vibration… Self-sensing function

Disadvantage: QCRs are vulnerable to stress concentration in bending.
# Conventional Sensors

## Comparison with Commercial Product and Previous Work

<table>
<thead>
<tr>
<th></th>
<th>(a) KISTLER 9001A</th>
<th>(b) KISTLER 9207</th>
<th>(c) Z. Wang et al. 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output</strong></td>
<td>Electric Charge</td>
<td>Electric Charge</td>
<td>Frequency</td>
</tr>
<tr>
<td><strong>Measuring Objects</strong></td>
<td>Quasi-static ~ Dynamic</td>
<td>Quasi-static ~ Dynamic</td>
<td>Static</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>4 pC/N (1 g)</td>
<td>115 pC/N (50 mg)</td>
<td>105 Hz/N</td>
</tr>
<tr>
<td><strong>Measuring Range</strong></td>
<td>~ 7.5 N</td>
<td>±50 N</td>
<td>~ 100 N</td>
</tr>
<tr>
<td><strong>Size [mm]</strong></td>
<td>φ10.3 x 6.5</td>
<td>φ11.9 x 63.7</td>
<td>31 x 30 x 35</td>
</tr>
</tbody>
</table>

Our goal is to make sensitive, wide range, small (thin) load sensor using AT-cut quartz crystal resonator.
Concept of Load Sensor

Characteristics of Vertical Type Load Sensor

1. Resolution improvement
   ⇒ Vertical type maintenance
2. Stable maintenance
   ⇒ Blade spring and outer casing
3. Further miniaturization
   ⇒ \( \phi 7 \times 11 \text{ mm} \)
   (1/4 volume ratio)

Packaging: more compact

\[
V_1 = \pi \times 3.5^2 \times 11 \text{ mm}^3 \\
V_2 = \pi \times 6.5^2 \times 13 \text{ mm}^3 \\
V_1 / V_2 = 0.25
\]

Contact point
Upper wall
Blade spring
Quartz crystal resonator
Casing
Outer casing
Ball bearing
Preloading bolt

Ref.) Narumi et al., JRM, 2009
**Structural Analysis**

**Stress distribution in z axis**

![Stress distribution in z axis diagram]

**Load Conversion Efficiency**

Section area of QCM: 0.1 mm x 3 mm = 0.3 m
Impressed load to QCM: 4.7 MPa x 0.3 mm$^2$ = 1.41 N
⇒ Load Conversion Efficiency: 1.41 / 2.0 = 0.705

cf. Load conversion efficiency of conventional sensor was 0.37.

**Stress distribution in y axis**

![Stress distribution in y axis diagram]

**Displacement distribution in y axis**

![Displacement distribution in y axis diagram]
Concept of Quartz Crystal Resonator

Fabrication Process

<table>
<thead>
<tr>
<th>(a) Resist spin coat</th>
<th>(d) Metal deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFPR LOR5B Cr/Au</td>
<td></td>
</tr>
<tr>
<td>(b) Exposure</td>
<td>(e) Removing</td>
</tr>
<tr>
<td>MASK</td>
<td></td>
</tr>
<tr>
<td>(c) Development</td>
<td>(f) Repeat (a)-(e)</td>
</tr>
</tbody>
</table>

Fig. 8 Fabrication process of QCR.
Fabrication -Retention Mechanism-

Fabrication of Retention Mechanism

Fabrication method: Wire electrical discharge machining
Material   - Casing: SUS304
- Blade Spring: Phosphor bronze

Fabricated retention mechanism and casing

Comparison with conventional sensor’s package
1. The sensor is pressed to wall by moving Z stage vertically.
2. The load given to the sensor is measured by load cell as the sensor and load cell are placed vertically.
3. Sensor output (resonance frequency) was measured by frequency counter.
### Experimental Results

#### With no Initial Load

- **Experiment condition**
  - Temperature: 22°C
  - Humidity: 45%
  - Voltage: 4.5 V

#### With Initial Load of 10 N

- **Experiment condition**
  - Temperature: 25°C
  - Humidity: 45%
  - Voltage: 4.5 V

Initial load is 10 N

\[ Y = 573.0 \times 10^{-6} X + 16.231 \]

*Y*: Resonant frequency [MHz]  
*R^2 = 0.9452*  
\[ X : \text{Load [N]} \]

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Discussion

Allowable stress to QCM is 128 MPa (38.4 N).
Resolution of the new type force sensor is seven times to the conventional one. (1250 / 160 = 7.8, 215 / 30 =7.2)

<table>
<thead>
<tr>
<th></th>
<th>New type sensor</th>
<th>Conventional type sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force conversion efficiency</td>
<td>70 %</td>
<td>37 %</td>
</tr>
<tr>
<td>Maximum load</td>
<td>38.4 x (100 / 70) = 54.9 N</td>
<td>38.4 x (100 / 37) = 103.8 N</td>
</tr>
<tr>
<td>Resolution</td>
<td>3.21 mN (0.33 g)</td>
<td>22.5 mN (2.30 g)</td>
</tr>
</tbody>
</table>

Comparison to measurement range

1 mN  | 10 mN  | 100 mN  | 1 N  | 10 N  | 100 N  |

Conventional type (Flat structure)

This sensor (Perpendicular Structure)
Application Examples
- Fundamental Research Field -
Temperature measurement for nanoscale object

Employ carbon nanotube as a tip of cantilever
Why CNT?

Graphene sheet with a cylindrical nanostructure

Ex) Single wall, Double wall, Multi wall carbon nanotube

- Small size (on the order of a few nanometers in diameter)

- High heat conduction (3000 ~ 6000 W/m·K), (cf: Cu 400 W/m·K)

- High stability

- High strength (up to 48,000 kN·m/kg),
  (cf: high-carbon steel's 154 kN·m/kg)

- High current density tolerance (10⁹ A/cm²)
  (cf: Cu 10⁶ A/cm²)
Thermal property of CNT


Purpose

Problem

High heat conduction (3000～6000 W/m・K )

Theoretical value

How about the flow of heat in water and air?

Purpose of this study

Evaluation of thermal characteristics
of CNT in air and water

How much is the value of the heat flow of
CNT actually in air and water?
Purpose

Detecting heat from the end of CNT

1. Heating at the end of CNT
   - Using microheater

2. Heat detection
   - Measuring electrical resistance by 4-point method
Design

Pattern on wafer

Chip size: 20 mm × 20 mm × 550 μm
(SOI Si:SiO₂:Si = 1.5 μm:3 μm: 550 μm)
Gap: 1 μm × 50 μm × 5 μm

(a) Overall view
(b) Top view
(c) Side view

Microheater
SOI wafer
Electrodes
Fabrication

Fabrication process

(a) Sputtering Cr/Au on SOI wafer

(b) Coating the EB resist

(c) Exposure

(d) Developing

(e) etching

(f) Removing the resist

(g) FIB etching

Nanomanipulator

(MM3A, Kleindiek Nanotechnik GmbH)

Fabricated pattern

MWNT (MTR Ltd.)
Experiments

CNT on the pattern
Measured result (water)

Heat quantity to increase the temperature of CNT in water (93.8 µJ/K) was lower than that in air (64.3 µJ/K)
Application Examples

- Bio Field -
Background

Disposable PDMS biochip

Cell

e.g. Oocyte 100-150μm

Loader Sorter

Incubation atmosphere

Arai et al. (2006-)

Automation system of supplying cells one by one from biochip to incubation atmosphere is highly required.
**Inkjet mechanism (EPSON Co., Ltd.)**

**Bio-printing (Nakamura et al.)**

### Problems

- **Cleaning** (Contamination)
- Cannot dispense a single cell

**Solution tank**

**Nozzle**

**Drive unit**
Automatic Cell Dispensing System for a single cell dispensing

Reversible inkjet mechanism

Disposable microchip

Air pulse generator

Loader

Air input

Microchannel

Nozzle

Capacitance sensor

Droplet with a cell

Culture well

XY-stage

Inkjet Mechanism with Disposable Structure
(JPN Patent: 2009-91542)

Ref.) Kawahara et al., μ-TAS, 2010
Capacitance Sensor

FEM analysis:

Particle

Capacitance sensor

Condition: $V_0 = V_{in}$
$\sin(2\pi ft)[V]$
$V_{in} = 0.1[V]$
$f = 100$ [kHz]
$t = 0 \sim 1e^{-5}$ (1e-8)

$$V_0 = V_{in} \sin(2\pi ft)[V]$$
$$V_{in} = 0.1[V]$$
$$f = 100 \text{ [kHz]}$$
$$t = 0 \sim 1e^{-5}$$

$$V = I \sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}$$
$$C = \frac{Q}{2V_0} = \frac{2\varepsilon_r \varepsilon_0 I}{\pi} \ln \left[1 + \frac{w}{a}\right] + \sqrt{\left(1 + \frac{w}{a}\right)^2 - 1}$$
**Fabrication Process**

1. **Nozzle**
   - 1. Drilling
     - Glass
     - Φ0.7mm
   - 2. Nozzle assemble
     - Ni nozzle
     - Φ0.3x0.7x2.0mm

2. **Electrode**
   - 1. Supatter (Cr/Au) & Resist patterning
     - Cr/A
     - OFPR
   - 2. Au wet etching
   - 3. Cr wet etching

3. **Micro-channel**
   - 1. PDMS molding
     - PDMS SU-8
   - 2. Assemble (Plasma)

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**Microchannel**
- Height: 600μm
- Width: 800μm
- Thickness: 195nm
- Height: 2mm
- Width: 300μm
Fabricated Microchip

Disposable microchip (30x30 mm)
Experimental Setup

Air pulse generator

Chip Holder

Culture well (XY)

Air source

Note PC (1ms)

DO AD RS-232C USB

ON/OFF

Sensor output

Position command

Image

Air pulse generator

Chip

Holder

Well

Camera

Culture well

XY

XYZ

Camera

XYZ

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Droplet generation and Dispensing

Droplet size: 1mm
Droplet volume: approx. 0.4μl

We succeeded in the single swine oocyte dispensing.
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