Micromechatronics
-A vital industrial technology in the new century

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OUTLINE

- Overview of mechatronics and micromechatronics
- Mechatronics – High value-added industrial technology
- Miniaturization – The prime driving force in 21st Century industrial technology
- Micromechatronics products
- Fundamental differences between micromechatronics and traditional mechatronics
- The many technical challenges in micromechatronics
- Nanoscale mechatronics
- Summary and conclusion
WHAT IS MECHATRONICS?

- Our perception

We view Mechatronics to be an engineering process that involves:

“Design and manufacture of intelligent products or systems that perform hybrid mechanical and electronic functions”
Industrial Products of MECHATRONICS

Mechatronics products can be:

- Robotic systems
- CNC Machine centers
- FMS, CIMs equipment
- Automatic wafer handling
- E-cameras, VCRs, DVDs
- Robotic systems
- CNC machine tools
- Mobile phones
- Hard disk drives
- Inkjet printer heads
- Guided missiles, satellites, space crafts
- Artificial organs

Intelligent products performing hybrid mechanical and electronic functions:

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The Multidisciplinary Nature of Mechatronics

- **Mechanical Engineering**
  - Mechanical Systems Design
  - Linkages and Mechanisms
  - Automatic Control

- **Electronic Engineering**
  - IC Manufacture
  - Electronic Packaging
  - Power supply
  - Circuit Design for Microprocessors & Microcontrollers
  - Special Purpose IC Design

- **Chemical Engineering**

- **Material Engineering**

- **Industrial Engineering**
  - Mechanical Design of Components & Peripherals

- **Computer Engineering**
  - Design of CPU’s, Microprocessors & Controllers
  - SW Interface

- **Mechatronic Systems Engineering**
  - Microcontrollers & Microprocessors

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High Value-Added Mechatronics Products

Hard Disk Drive – A typical mechatronics product:

Key electromechanical engineering subjects:

- Aerodynamics: flight height control
- Acoustics and vibration: low noise and dimensional stability
- Precision machine design: tight tolerances between spinning and stationary parts
- Servo-mechanisms: precision motion control of read/write head
- Tribology: friction and wear between disk surfaces and read/write head during start-up and shut-down
- Thermal management: heat generation and dissipation in sealed enclosure
- Integration of microelectronic circuits for control and signal processing
High Value-Added Mechatronics Products – cont’d

The inkjet printer head:

- Injection nozzles
- Ink well
- Electric metal foil heater

Equilibrium State:
- Instantaneous electrical heating:
  - Local vaporization of ink:
    - Ejection of ink by vapor pressure:

Key technologies:
- Fluid dynamics
- Two-phase heat transfer
- Precision controls on:
  - Heating of ink well,
  - Proper nozzle openings and closing
- Electronics control

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Intelligent Robots –
A Current Major Development in Mechatronics

Major Applications:

- **Biomedical:** Surgical tools (e.g. laparoscopic tools)
  Medical diagnosis (e.g. colonoscopy)
  Drug delivery with automated dispensing
- **Surveillance, search and rescue by robot troops:**
- **Health care:** Humanoid robots for assisted living of the elderly
  (nursing, cooking, feeding, bathing, dressing, house cleaning, security, shopping, etc.)
- **Industrial production works** involving hazardous working environment
  and of repetitive nature using humanoid robots

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Humanoid Robots

- A nice “mechatronics couple” at Waseda University, Tokyo, Japan

Principal requirements for humanoid robots:
- Must be harmless and safe to human
- Able to learn, comprehend and act by rules
- Built on rule-based artificial intelligence with inference engine
- With vision and voice recognition/synthesis and communications
- With dexterous and strong limbs and hands
- Wireless power supply and communications

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Micromechatronics

Micromechatronics =

Devices or engineering systems performing electromechanical functions, with components in \( \mu m \) \((10^{-6} \ m)\) or sub-\( \mu m \) \((nm = 10^{-9} \ m)\) scale
Driving Force behind Micromechatronics

Increasing strong market demand for:

“Intelligent,”

“Robust,”

“Multi-functional,” and

“Low-cost” industrial products.

Micromechatronics can satisfy such market demand

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Miniaturization - The Evolution of Mobil Telephones

Mobil phones 20 Years Ago: Transceive voice only

Current State-of-the Art:

- Wireless cell phones
- Size reduction
- Advanced mobile phone – the i-phone
- Transceive voice + multi-media + Internet
- Web browser + email
- (stationary and video camera, calendar, calculator, GPS mapping, stock market information, down-loading music, movies, TV, video games)

The only solution is to pack many miniature functional components into devices with reduced sizes

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MEMS and Microsystems Technology (MST) (1 µm - 1 mm)

A top-down approach:
Initiated in 1947 with the invention of transistors, but the term “Micromachining” was coined in 1982

A bottom-up approach:
Inspired by Richard Feynman’s speech in 1959***, with active R&D began in around 1995. There is a long way to building nanoscale devices!

Nanotechnology (NT) (0.1 nm – 0. 1 µm)

* 1 µm = 10⁻⁶ m ≈ one-tenth of human hair
** 1 nm = 10⁻⁹ m ≈ span of 10 H₂ atoms
*** “There’s Plenty Room at the Bottom,” Annual meeting of the American Physical Society, California Institute of Technology, December 29, 1959.
Representative Microsystems Technology (MST) Products*

**Microsensors:**
- Acoustic wave sensors
- Biomedical and biosensors
- Chemical sensors
- Optical sensors
- Pressure sensors
- Stress sensors
- Thermal sensors

**Microactuators:**
- Grippers, tweezers and tongs
- Motors - linear and rotary
- Relays and switches
- Valves and pumps
- **Optical equipment** (switches, lenses & mirrors, shutters, phase modulators, filters, waveguide splitters, latching & fiber alignment mechanisms)
- **RF MEMS** (oscillators, varactors, switches)

**Microsystems = sensors + actuators + signal transduction:**
- Vehicle airbag deployment systems
- Hard disk drives (Read/Write heads)
- Inkjet printer heads
- Microfluidics, e.g. Capillary electrophoresis (CE)
- Drug delivery systems with micro pumps and valves

* Most MST products perform electromechanical-biological-chemical functions

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Applications of MEMS and Micromechatronics by Industries

Aerospace industry:
- Command and control systems (e.g. miniature smart sensors and actuators)
- Communications and radar systems (e.g. broadband, low resistance RF switches)
- Engine performance (e.g. sensors for high performance propulsion control systems)
- Inertial guidance and navigation systems (e.g. microgyroscopes)
- Micro and pico satellites

Automotive Industry:
- Safety (e.g., airbag, antilock braking systems, collision avoidance sensors)
- Engine and power train (e.g., manifold absolute pressure sensors)
- Comfort and convenience (e.g., automatic seat adjustment, telematic systems)
- Vehicle diagnostics and health monitoring

Biomedical industry:
- Biomedical instruments and surgical equipment
- Drug discovery and delivery
- Medical diagnosis (e.g. sensors and analytic systems)

Telecommunication industry:
- Optical switching and fiber-optic couplings
- RF wireless switches, tuners, oscillators, filters, etc.
- Tunable resonators

Consumer products (toys, telematics, recreational devices, smart appliance sensors, etc.)
The Lucrative Micromechatronics Markets

Microsystems technology:
$43$ billion - $132$ billion* by Year 2005
(*High revenue projection is based on different definitions used for MST products)

Nanotechnology:
$50$ million in Year 2001
$26.5$ billion in Year 2003
(if include products involving parts produced by nanotechnology)

$1$ trillion by Year 2015 (US National Science Foundation)

An enormous opportunity for manufacturing industry!!

• There has been colossal amount of research funding to NT by governments of industrialized countries around the world because of this enormous potential.
Micromechatronics

vs.

Traditional Mechatronics
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Challenges in Micromechatronics Technology

- Manufacturing and production
- Electromechanical Design
- Control theories
- Microassembly
- Packaging
- Testing and reliability
Micromechatronics Manufacturing
by physical-chemical-biological processes
Clean-room Operations

Traditional Manufacturing
by machine tools
CNC Machine Center

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Challenge in Electromechanical Design

- 3-D microstructure between 1 µm – 1 mm << size of human hair
- Innovative structure configurations for minute available space
- Applied load with non-conventional forces:
  - Electrostatic forces
  - Piezoelectric forces
  - Inter-granular forces
  - van der Waals forces
  - Molecular forces in sub-µm scale
- Thin film mechanics analysis
- Interlaminar (fracture) mechanics for multi-layered structures
- Integration of microstructural design and microelectronics (CMOS)
Micromechatronics systems design also includes:

- Signal transduction
- Fabrication processes and manufacturing techniques
- Assembly and packaging of all minute parts and components
- Reliability and testing
Case of micromechatronics systems design

(1) Innovative structure configurations, and
(2) Integration of microsystems and microelectronics

Inertial sensor:
2 mm x 3 mm
by Analog Devices

µ-devices:
µ-accelerometers

CMOS ICs
(>80% Foot Print)

Acceleration
Proof Mass
Fixed electrode
Floating electrode
Tether Springs

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Challenge in Motion Control Theory Development

Micromechatronics components have negligible mass (negligible mechanical inertia), but with complex driving forces.

The equation of motion for developing control algorithm has to cope with situations:

\[ m \frac{d^2u(x)}{dx^2} + c \frac{du(x)}{dx} + ku(x) = F(x) \approx 0 \]

Actuation Forces
- Electrostatic force (Instant but low in magnitudes)
- Piezoelectric force (Large magnitude in short time)
- Thermal force (Largest sustained but slow in generation)

Intrinsic Forces
- Atomic force (van der Waals force)
- Surface tension (due to humidity)
- Inter-molecular forces

None of these forces can be readily quantified or controlled

Intelligent control of micromechatronics is a relative “virgin” land – a reason for lack of intelligence of micromechatronics products

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Packaging and Assembly of Micromechatronics Systems

A Major Challenge to Engineers and Scientists
Micromechatronics systems packaging is a major cost factor in the product development.

Packaging cost can be as high as 95% of the overall production cost.

On average, packaging cost is between 20 – 50% of the total development cost.

- Cost-effective packaging and assembly of micromechatronics products and systems is thus the key to success of such products and systems in the marketplace.
(1) The minute delicate core elements are often required to interface with environmentally unfriendly and erosive working media – an “INTERFACE” problem

(2) Many micromechatronics devices require hermetic sealing from external environment, yet allowing moving components to be packaged inside the device, e.g. micro optical switches

(3) The core elements of many micromechatronic systems are expected to generate a variety of signals in electromechanical, biological, optical and chemical forms

   These signals need to be converted and transmitted to outside terminals

(4) Seamless integration of microelectronics and micromechatronics is a major task in systems packaging

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Assembly of Micromechatronics Systems

- Assembly of minute and delicate components requires microscale tolerances

- Highly labor-intensive: Most microassembly jobs are handled manually under microscopes

- Microassembly is thus a major stumbling block in mass production of micromechatronics systems or products
Major Technical Problems in Micromechatronics Systems Assembly

- **Setting proper tolerances:**
  - Alignments
  - Insertions
  - Joining

- **Tools and fixtures for short working distance under microscopes:**
  - Working distance under microscope reduces drastically with magnifications (often in a few mm)
  - Microgrippers or tweezers working in narrow space often have aspect ratio exceeding 100:1 → dimensional instability
  - Tools operates under extreme precision with resolution in nm

- **Difficulty in microgripper design:**
  - Requires precise control of grasping forces with real-time feedback to compensate errors induced by coupled electromechanical effects
  - Requires effective yet fast response in gripping (thermal vs. electrostatic actuating forces)
  - Overcome adhesive forces when releasing the object in pick-n-place operations

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Adhesive Forces in Micrograsping

- Gravitation of minute objects is insignificant in pick-n-place operations. As such, induced adhesive forces may dominate in these operations.

- These adhesive forces cause great difficulty in releasing the object at the end of the operation:

Grasping:

- Flat Gripper Arms
- Gripping Force
- Gravitation (insignificant)

Releasing:

- Adhesive Force
- Gravitation

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Adhesive Forces in Micrograsping

- There are two principal contributing sources for the adhesive forces:
  - van der Waals force, and
  - Electrostatic force.

- In wet assemble, or assembly in humid environment, the “surface tension” of the fluid between the contacting surfaces become the 3rd adhesive force component.

- Exact quantification of these forces is not possible.

- Use a case involving Pick-n-Placing a sphere by a pair of flat plate gripping arms for assessing the adhesive forces:
Adhesive forces in Pick-n-Placing of a sphere by a pair of flat plate gripping arms:

(1) **van der Waals force** \(d < 100 \text{ nm}, \text{ or } 0.1 \mu\text{m}\):

\[
F_v = \eta \frac{H d}{16\pi \delta}
\]

where \(H\) = Lifshitz-Van der Waals constant = 1-10 eV.
\(\delta\) = atomic separation between the contacting surfaces.
\(\eta\) = correction factor for rough surfaces (\(\approx 0.01\))

(2) **Electrostatic force** \(10 \mu\text{m} < d < 1 \text{ mm}\):

Induced in picking portion of the process due to charge-generation, or charge-transfer during the contact.

\[
F_e = \frac{q^2}{4\pi \varepsilon d^2}
\]

where \(q\) = electrostatic charge; \(\varepsilon\) = permittivity of the dielectric.

Approximate charge density in micro gripping is \(1.6 \times 10^{-6} \text{ C/m}^2\).

(3) **Total adhesive force in “dry” assembly:**

\[
F = F_v + F_e
\]
Challenge on Reliability in Micromechatronics Products

The critical issue of reliability is that no matter how big or small, or how sophisticated the product is designed and manufactured - it becomes **useless** if it fails to deliver the designed performance during the expected lifetime.

Reliability of Micromechatronics products is particularly critical as **failure** of many of these products can be **catastrophic** and **devastating**.

Because reliability is such a critical issue in MEMS and microsystems, design alone cannot ensure the reliability of the product.

**Logical design + reliable testing strategies + enabling testing techniques**

= **Assurance of reliability of the product**

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Failure mechanisms for microsystems are much more complicated than those in microelectronics for the following reasons:

- Microsystem components are designed to interact with various substances (e.g., light beams, chemical solvents and biological fluids) at various environmental conditions (temperatures and pressures).

- Many micromechatronics products are hermetically sealed and are expected to perform in both immediate- and long-term.

- Some failure of microsystems is impossible to predict and prevent, e.g., the stiction of delicate components in micro-optical switches with sealed plastic package, induced by slow release of moisture (de-gassing) of plastic encapsulating materials.

- New testing procedures and criteria need to be developed for every new product.

- It’s a major challenge to design engineers and the industry

  - Reliability of micromechatronics products is another major stumbling block in successful commercialization.
Challenge in Engineering Design of Nanoscale Mechatronics Device Components

Major challenge in design analyses:
(1) Strong size-dependent material properties
(2) All cases are time-dependent

Analytical Design Formulation:
• **Molecular Heat Transfer**
  (Thermal actuation of nanoscale devices, heat dissipation and packaging of molecular electronics)
• **Molecular Gas Dynamics**
  (Nanofabrication process of CVD, plasma etching and cooling of molecular electronics)
• **Molecular Dynamics Simulation**
  (Design of nanoscale sensors and actuators, packaging of molecular electronics)

Nanofabrication:
Nano printing and nanomanufacturing

Nanoassembly – assemble nanoscale structures on atom-by-atom bases

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Summary on Molecular Heat Conduction

Heat conduction in solids requires *carriers*.

Heat transportation in solids of in sub-micron and nano scales is predominantly done by the “flow” of *phonons*.

There are *collisions and scattering* of free-phonons take place at all times during heat transmission:

The average “**mean free path**” (MFP):

\[
\lambda = \frac{d_1 + d_2 + d_3}{3}
\]

The average “**mean free time**” (MFT):

\[
\tau = \frac{(t_2 - t_1) + (t_3 - t_2) + (t_4 - t_3)}{3} = \frac{t_4 - t_1}{3}
\]
Summary on Molecular Heat Conduction – cont’d
(For solid size, $H < 7\lambda$)

The thermal conductivity, 
\[ k = \frac{1}{3} CV\lambda \]

Parameters for Thermal Conductivity of Thin Films
[Flik et.al. 1992 and Tien and Chen 1994]

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dielectric and semiconductors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heats, $C$</td>
<td>Specific heat of electrons, $C_e$</td>
</tr>
<tr>
<td>Molecular velocity, $V$</td>
<td>Electron Fermi velocity, $V_e \approx 1.4 \times 10^6$ m/sec</td>
</tr>
<tr>
<td>Average mean free path, $\lambda$</td>
<td>Electron mean free path, $\lambda_e \approx 10^{-8}$ m</td>
</tr>
</tbody>
</table>

Example: With an average value of $\lambda_e = 10^{-7}$ m for phonons, the $k$ for 0.2 $\mu$m Si film is only 83% of the same property of Si in macro scale.

The heat conduction equation:
\[ \nabla^2 T(\vec{r},t) + \frac{Q}{k} = \frac{1}{\alpha} \frac{\partial T(\vec{r},t)}{\partial t} + \tau \frac{\partial^2 T(\vec{r},t)}{\partial t^2} \]

where the “relaxation time, $\tau$ is:
\[ \tau = \frac{\lambda}{V} \]

in which $V$ is the average velocity of the heat carrier.

The value of $\tau \approx 10^{-10}$ seconds for semiconducting materials.
Overview of Molecular Gas Dynamics

- Gas dynamics derived from continuum theory breaks down at scale less than 1 micron (or < 1000 nm).
- Molecular physics governs.
- Gas flow in this scale is “rarefied”.
- “Mean free path” (MFP) and “Mean free time” (MFT) dominate in energy transportation.
- Knudson number (Kn) and Mach number (Ma) characterize the flow.
- $\text{Kn} = \frac{\text{MFP} (\lambda)}{\text{Characteristic length} (L)}; \lambda \approx 65 \text{ nm}$
  $\text{Ma} = \frac{\text{Speed of sound in the rarefied gas}}{\text{Speed of sound at standard conditions}} (\text{Ma} < 0.3)$
Modeling of Molecular Gas Dynamics

- $K_n = \text{MFP} (\lambda)/\text{Characteristic length (L)}$; $\lambda \approx 65 \text{ nm}$ for most gases
- $Ma = \text{Speed of sound in the rarefied gas}/\text{Speed of sound at standard conditions}$

### Modified Navier-Stokes Equation
- Can be used for $0.01 < K_n < 0.13$.
- New gas dynamics theory and formulations need to be developed for nano scale gas flow with $K_n > 0.13$. 

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Molecular Dynamics in Engineering Design of Nanoscale Structures

It determines:

(1) The required forces (or energy) to move single atoms (or molecules) in a molecular force field.

(2) The motion of individual atoms (or molecules):
   Trajectories (Positions, Velocities and Orientations) when subject to external force field.

(3) The Schrodinger’s equation (1926) is used as the basic governing equation for the”deterministic” molecular dynamics.
Elements of Molecular Dynamic Simulation

Principal Modules:
• Equation of Motion
• Environmental Interactions
• Molecular Interactions

Sub-modules:
• Dynamic equilibrium with applied forces and energies
• Dynamic and static properties
• Molecular trajectories (soft or hard sphere collision)
• Phase-space trajectories for vibrating molecules
• Distribution functions of sample molecules in 2-D and 3-D (velocities, properties, etc.)
• Periodic boundary conditions

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The Schrödinger Equation
for Nonrelativistic Quantum Mechanics (1926)

The position of a charged particle, \( \phi(\vec{r}, t) \) in a force field of \( N \)-charged particles with masses, \( m_0, m_1, m_2, \ldots, m_{N-1} \) can be obtained from the following equation:

\[
-\frac{\hbar^2}{2} \sum_j \frac{1}{m_j} \frac{\partial^2 \phi(\vec{r}, t)}{\partial r_j^2} + U(\vec{r}, t)\phi(\vec{r}, t) = i\hbar \frac{\partial \phi(\vec{r}, t)}{\partial t}
\]

where \( \vec{r} \) = position vector, or the coordinates
\( U(\vec{r}, t) \) = potential energy function
\( \hbar \) = the Planck constant

The inter-molecular force on molecule \( i \) caused by \( N-1 \) other molecules is:

\[
\vec{F}_i = -\frac{\partial \phi(\vec{r}, t)}{\partial \vec{r}}
\]
Summary

● Market demand for “Smaller”, “Smart”, “Multi-functional”, and “Low cost” engineering systems and consumer products will be even stronger in times.

● Further miniaturizing mechatronics systems is unavoidable. Both “top-down” approach (Microsystems technology) and “bottom-up” approach (Nanotechnology) will be used in this development.

● Nanoscale mechatronics systems (NEMS) appears long way from reality.

● Principal application of micromechatronics will be in biomedical and healthcare fields, in particular, in:
  ● in-vivo real-time monitoring;
  ● disease diagnosis;
  ● drug delivery and dispensing;
  ● drug discovery and production;
  ● microsurgical tools;
  ● artificial organs.
Future Outlook of Micromechatronics

- Critical research areas in mechatronics in biomedical and healthcare:
  - humanoid robots and robots with high ratio of workspace to own size;
  - reliable power supply and efficient power consumption;
  - wireless motion and process control technology.

- Major challenges to mechatronics engineers:
  - new control systems for micro- and nanoscale mechatronics systems
  - nanoscale electromechanical actuation materials
  - integration of micro-nanoelectronics with micro-nanoscale systems
  - cost-effective APT (Assembly-Packaging-Testing) for micro- and nanoscale mechatronics systems

There is virtually unlimited opportunities in micro- and nanoscale mechatronics for business and industry in this New Century