1. TOYOTA CRDL, INC

Automotive Industry and MEMS Technology

Yutaka NONOMURA
Principal Researcher
System & Electronics Engineering Dept. III
TOYOTA CENTRAL R&D LABS., Inc.

Outline

1. TOYOTA CRDL, INC
2. Sensing Technology for Automobiles
3. Sensors for Automobiles
   3.1 Combustion Pressure Sensor
   3.2 Quartz Yaw Rate Sensor
   3.3 3-Axis Accelerometer
   3.4 Optical Device
4. Sensors for Robots
   4.1 Robot Use of Automotive Sensors
   4.2 Tactile Sensor with Nerve Network
5. Summary
Company Outline

- **Established**: November 1960
- **Location**: Nagakute, Aichi, Japan
- **Capital**: 3 billion yen (30 million US$)
- **Number of Employees**: 1,035
- **Ground Area**: About 300,000 m²
- **Floor Space**: About 98,000 m² (March 2014)

Stockholder Companies & Technical Collaboration Contractor Companies

Stockholder Companies
- Toyota Industries Corporation
- Toyota Motor Corporation
- Aichi Steel Corporation
- JTEKT Corporation
- Toyota Auto Body Co., Int.
- Toyota Tsusho Corporation
- Aisin Seiki Co., Ltd.
- Denso Corporation
- Toyota Boshoku Corporation

Technical Collaboration Contractor Companies
- Toyota Motor East Japan, Inc.
- Toyoda Gosei Co., Ltd.
- Hino Motors, Ltd.
- Daihatsu Motor Co., Ltd.

Other 39 companies

From automatic loom to automobile

Technological History 1

- 1960: Toyota CRDL, Inc. established in Nagoya City
- 1972: Thermo-Reactive Deposition and Diffusion Process (TRD Process)
- 1975: Exhaust Gas Purification System, Oxygen Sensor
- 1980: Expanded and Transferred to Nagakute
- 1982: T-10 Robot
- 1987: Sound Quality of Car Interior Engine Noise
- 1990: Nylon-Clay Hybrid (NCH)
- 1997: Reaction Control Technology under Shear Flow (Rubber Recycling), Insulated Gate Bipolar Transistor (IGBT) and Diode for Hybrid Vehicles

Technological History 2

- 2000: Toyota Unveils Cyber Humanoid Body for Research of Accident Injuries (THUMS®), GUM METAL (Published in Science 2003)
- 2001: Visible-Light Active Photocatalyst (Published in Science 2001)
- 2004: Ultrahigh-Quality Silicon Carbide Single Crystals (Published in Nature 2004), High Performance Lead-free Piezoelectric Materials (Published in Nature 2004), DLC-Si Coating Process
- 2005: Inertial Force Sensing System for Mobility Robots
- 2009: Pedestrian Detection for Night View System
- 2010: Noble Metal Sintering Suppression Technology in Exhaust Catalyst
- 2011: Solar Fuels - CO₂ Photoconversion into Organic Compounds
2. Sensing Technology for Automobiles

Configuration of VDIM:

**VDIM:** Vehicle Dynamics Integrated Management

**CAN:** Control Area Network

Network of sensors, computers, & actuators

from History of 75 year TOYOTA Motors

more than 100 sensors

**Sensor Application Comparison**

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Home Electronics</th>
<th>Industry</th>
<th>Airplane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>0.1 to 1 %</td>
<td>0.1 to 1 %</td>
<td>0.1 to 1 %</td>
</tr>
<tr>
<td><strong>Temperature Range</strong></td>
<td>-65 to 70 °C</td>
<td>0 to 80 °C</td>
<td>0 to 80 °C</td>
</tr>
<tr>
<td><strong>Vibration</strong></td>
<td>0.0 to 5 G</td>
<td>0 to 5 G</td>
<td>0.05 to 10 G</td>
</tr>
<tr>
<td><strong>Power Fluctuation</strong></td>
<td>+/- 10 %</td>
<td>+/- 10 %</td>
<td>+/- 10 %</td>
</tr>
<tr>
<td><strong>EMC</strong></td>
<td>Large</td>
<td>Medium</td>
<td>Small</td>
</tr>
<tr>
<td><strong>Ambient</strong></td>
<td>Water, Oil, Erosion</td>
<td>Water, Oil, Erosion</td>
<td>Water, Salt</td>
</tr>
<tr>
<td><strong>Sensor Cost</strong></td>
<td>1 to 10 ¥</td>
<td>10 to 100 ¥</td>
<td>100 to 1000 ¥</td>
</tr>
<tr>
<td><strong>Whole Cost</strong></td>
<td>0.001 to 0.1 ¥/m</td>
<td>0.001 to 1 ¥/m</td>
<td>0.1 to 1 ¥/m</td>
</tr>
<tr>
<td><strong>Cost Ratio</strong></td>
<td>10^3 to 10^6</td>
<td>10^3 to 10^6</td>
<td>10^3 to 10^6</td>
</tr>
<tr>
<td><strong>Mass Production</strong></td>
<td>Public, Professional</td>
<td>Public, Professional</td>
<td>Professional</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
</tr>
</tbody>
</table>

**Accuracy:** Middle  
**Working range:** Wide  
**Life:** Long

High stability  
High reliability  
Low cost by mass production

Kind of Automotive Sensor

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Water, Oil, Intake, Exhaust air, Fuel, Cabin</th>
<th>Oxygen, Lean, NOx, HC, H2</th>
<th>Intake air, Air flow, Combustion, Supercharging, Brake, Tire, Compressor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td>Gas</td>
<td>Pressure</td>
<td>Position</td>
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</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>Speed</td>
<td>Acceleration</td>
<td>Force, Load</td>
</tr>
<tr>
<td><strong>Position</strong></td>
<td>Angle</td>
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<tr>
<td><strong>Angle</strong></td>
<td>Speed</td>
<td>Force, Load</td>
<td>Vibration</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>Angular rate</td>
<td>Vibration</td>
<td>Light, Electric wave, Sound</td>
</tr>
<tr>
<td><strong>Angular rate</strong></td>
<td>Acceleration</td>
<td>Vibration</td>
<td>Light, Electric wave, Sound</td>
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<td><strong>Acceleration</strong></td>
<td>Force, Load</td>
<td>Vibration</td>
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<td>Vibration</td>
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<tr>
<td><strong>Vibration</strong></td>
<td>Light, Electric wave, Sound</td>
<td>Light, Electric wave, Sound</td>
<td>Light, Electric wave, Sound</td>
</tr>
<tr>
<td><strong>Light, Electric wave, Sound</strong></td>
<td>Laser, Microwave, Visible light, IR light</td>
<td>Solar irradiation, Headlight, Voice, Ultrasound</td>
<td>Light, Electric wave, Sound</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td>Glow plug, Particle, Rain drop, Humidity, Antenna, Fingerprint, Current</td>
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<td>Glow plug, Particle, Rain drop, Humidity, Antenna, Fingerprint, Current</td>
</tr>
</tbody>
</table>

Inner sensor: Pressure, Acceleration, Angular rate (very important to control vehicle)  
Outer sensor: Sonar, Rader, Vision (expecting advanced safety)
3. Sensors for Automobiles

3.1 Combustion Pressure Sensor
Combustion Pressure Sensor

for Low Exhaust Emission
for Low-fuel Consumption

Lean Burn Engine (TOYOTA) 1993

Prize of Japan Society of Mechanical Engineers

from Y. Nonomura et al., IMechE (1994)

TOYOTA CRDL., INC.

Combustion Pressure Sensor

Installed on TOYOTA Lean Burn Engine in 1993

Cross Section View

Cross Gauge Type

Piezoresistive effect of Semiconductor single crystal Si

from Y. Nonomura et al., IMechE (1994)

TOYOTA CRDL., INC.

Combustion Pressure Sensor

Piezo-resistive effect of Semiconductor single crystal Si

from Y. Nonomura et al., IMechE (1994)

TOYOTA CRDL., INC.

Combustion Pressure Sensor

Waveform of combustion pressure

from Y. Nonomura et al., IMechE (1994)

TOYOTA CRDL., INC.
3. Sensors for Automobiles

3.2 Quartz Yaw Rate Sensor

What is VSC

Generate anti-spin force and the vehicle runs safely

SPIN DETECTION

SPIN CONTROL

ROTATION

REVOLUTION

ANT-SPIN FORCE

ROTATION

SAFETY

SPIN

Without normal brake

With normal brake

Detection of the Coriolis Force

\[ F_c = 2 m \vec{V} \times \vec{\Omega} \]

\( m \): MASS
\( \vec{V} \): VELOCITY
\( \vec{\Omega} \): ANGULAR RATE

High-quality artificial crystal (made in Japan)
Tuning fork

Principle of the Vibration Sensor

Structure of Quartz Sensor

Electrode

Quarz Vibration Element

Piezoelectric effect (Intrinsic Polarization)

Excitation

Detection

Fixed Part

CROSSSECTION of VIBRATOR

(15 x 3.5 x 0.3 mm³)
3. Sensors for Automobiles

3.3 3-Axis Accelerometer

An SOI 3-Axis Accelerometer with a Zigzag-shaped Z-electrode for Differential Detection

Motivation

- A highly-accurate and reliable 3-axis accelerometer is required for automobiles and robots control.
- Differential detection for Z-axis is essential to improve the accuracy of the accelerometer.

Zigzag-Shaped Z-electrode (ZSZ)

- Differential detection for Z-axis is achieved with only two Si layers.
- Gap distances 1-3 are equal by the uniformity of the oxide layer.
1. SOI* for sensor material
2. All translational motion detection
3. Zigzag-Shaped Z-electrode (ZSZ)

- SOI 3-Axis Accelerometer with ZSZ
- Zigzag-Shaped Z-electrode was primarily proposed for 3-axis accelerometer with differential detection.

3-Axis Accelerometer

VSC (Vehicle Stability Control)
VDIM (Vehicle Dynamics Integrated Management)

3. Sensors for Automobiles
3.4 Optical MEMS
MEMS Scanner

perimeter monitoring mirror for laser radar
TOF (time of flight)
large mirror size
8x4mm
2-axis drive
moving magnet
one permanent magnet
mirror angle detection
by Hall element

Structure of MEMS Scanner

Mechanical rotation angle

Driving condition
-frame (non-resonance): 30 Hz, 700mA
-mirror (resonance): 1.3 kHz, 19mA

Characteristics of MEMS Scanner

4. Sensors for Robots
4.1 Robot Use of Automotive Sensors

Toyota Group has a dream
to create a new world and style of life with robots as partners.
Role of the Artificial Three Semicircular Canal

- Person
- Artificial Three Semicircular Canal (Gyro)
- Biped-type Robot
- Rolling-type Robot (Inverted Pendulum)
- IMU: inertial measurement unit

Robots with the Inertial Force Sensing System

- Biped-type Robot (Plays the Trumpet)
- Rolling Type (2 + 1 wheels) <i-Swing>
- Rolling Type (2 wheels) Robot

Artificial Three Semicircular Canal with three gyro sensors, three acceleration sensors, and a digital signal Processor

4. Sensors for Robots

4.2 Tactile Sensor with Nerve Network
Nerve Net Type Tactile Sensor

<POINTS>
Serial bus, Event driven against congestion
Sensor chip on signal processor
Signal outputs when force changes
Nerve like relay node

from M. Makihata, Y. Nonomura, et al. Transducers 2011

Structure of Tactile Sensor Element
- triaxial force detection with seesaw electrode
- complete differential detection
- electrostatic capacitance detection
- SOI (Silicon on Insulator) substrate stable material
- integrated architecture
- sensor element and LSI

from Y. Hata, Y. Nonomura, et al., MEMS 2014

Characteristic of Sensor Element

from Y. Hata, Y. Nonomura, et al., MEMS 2014

5. Summary

- The sensors for the automobiles have been advanced with the MEMS technology.
- New sensors and devices are created with new MEMS technology, and that will continue to grow.
- The needs and applications of the sensors and devices are expanding.
- The sensors and devices of the automobiles should be integrated with LSI for high performance and communication systems.