Automotive Industry and MEMS Technology

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TOYOTA CENTRAL R&D LABS., Inc.

Outline

1. TOYOTA CRDL, INC

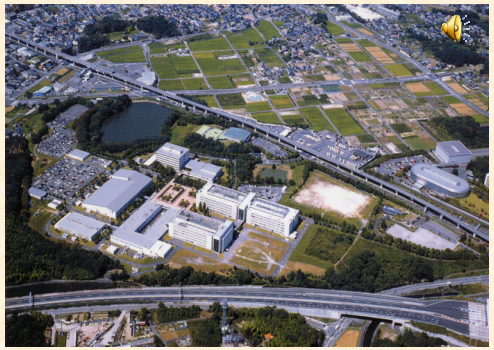
Introduction of Toyota Central Research and Development Laboratories, Incorporated

March 2014

Company Outline

- Established :November 1960
- Location :Nagakute, Aichi, Japan
- Capital :3 billion yen (30million US$)
- Number of Employees :1,035
- Ground Area :About 300,000 m^2
- Floor Space :About 98,000 m^2

(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

9 companies

From automatic loom to automobile

Technical Collaboration Contractor Companies

- Toyota Motor East Japan, Inc.
- Toyoda Gosei Co., Ltd. — Blue light emitting diode
- Hino Motors, Ltd. — Truck
- Daihatsu Motor Co., Ltd. — Light automobile

Other 39 companies

(March 2014)

Technological History 1

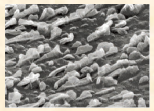
- 1960: Toyota CRDL, Inc. established in Nagoya City
- 1972: Thermo-Reactive Deposition and Diffusion Process (TRD Process)
- 1975: Exhaust Gas Purification System, Oxygen Sensor

The first feedback system with an electric sensor

Exhaust Gas Purification System catalyst

- 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

T-10 Robot



SEM image of NCH

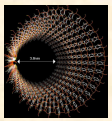
Rubber Recycling

IGBT

Technological History 2

- 2000: Toyota Unveils Cyber Humanoid Body for Research of Accident Injuries (THUMS®), GUM METAL (Published in Science 2003)

THUMS®



CG image of the Mesoporous Organosilica

- 2001: Visible-Light Active Photocatalyst (Published in Science 2001)

Visible-Light Active Photocatalyst

- 2002: An Ordered Mesoporous Organosilica Hybrid Material with a Crystal-Like Wall Structure (Published in Nature 2002)
- 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

DLC-Si Coating Process

Inertial Force Sensing System and Robot using the system

- 2005: Inertial Force Sensing System for Mobility Robots

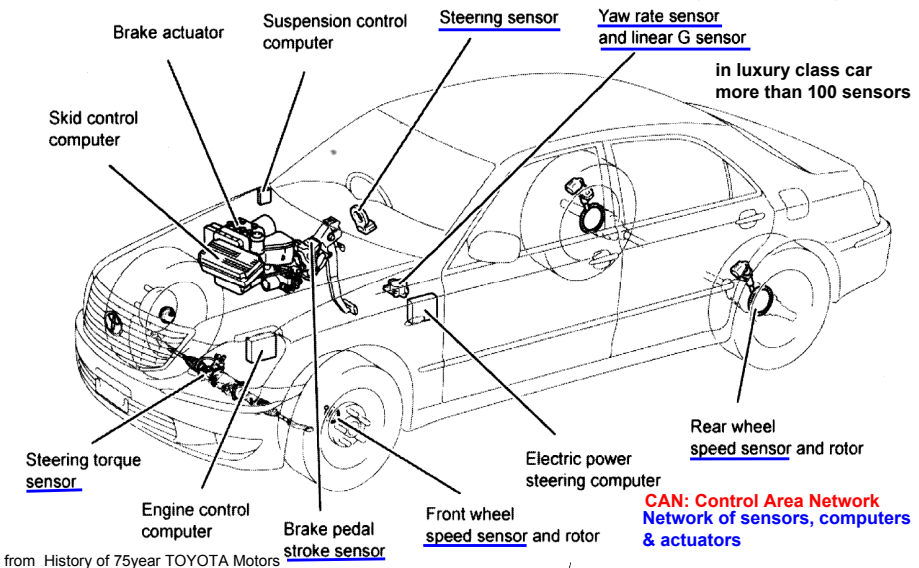
Pedestrian Detection for Night View System

- 2009: Pedestrian Detection for Night View System
- 2010: Noble Metal Sintering Suppression Technology in Exhaust Catalyst
- 2011: Solar Fuels -CO_2 Photoconversion into Organic Compounds

2. Sensing Technology for Automobiles

Configuration of VDIM

VDIM : Vehicle Dynamics Integrated Management



from History of 75year TOYOTA Motors

Sensor Application Comparison

	Automobile	Home Electronics	Industry	Airplane
Accuracy	1 to 5 %	5 to 20 %	0.1 to 1 %	0.1 to 1%
Temperature Range	-40 to 120 ℃	-10 to 50 ℃	0 to 60 ℃	-55 to 70 ℃
Vibration	2 to 25 G	1 to 5 G	0 to 5 G	0.5 to 10 G
Power Fluctuation	+/- 50 %	+/- 10 %	+/- 10 %	+/- 10 %
EMC	Large	Small	Medium	Small
Ambient	Water, Salt, Dirt, Erosion	Water	Water, Oil, Erosion	Water, Salt
Sensor Cost	1 to 10 $	1 to 10 $	10 to 100 $	100 to 1000 $
Whole Cost	0.01 to 0.1 M$	0.001 to 0.01 M$	0.001 to 1 M$	0.1 to 100 M$
Cost Ratio	10^2 to 10^5	10^1 to 10^4	10^1 to 10^5	10^2 to 10^5
Mass Production	Good	Good	Poor	Poor
Maintenance	Public, Professional	Public, Professional	Professional	Professional

EMC: electromagnetic compatibility

Accuracy: Middle
Working range: Wide
Life: Long

High stability
High reliability
Low cost by mass production

Kind of Automotive Sensor

Temperature	Water, Oil, Intake, Exhaust air, Fuel, Cabin
Gas	Oxygen, Lean, NO_x, HC, H_2
Pressure	Intake air, Air flow, Combustion, Supercharging, Brake, Tire, Compressor
Position	Fuel level, Cam, Vehicle height, Seat
Angle	Crankshaft, rotation, Throttle, Steering, Direction
Speed	Engine, Vehicle, Transmission, Wheel
Angular rate	Yaw rate, Rollover
Acceleration	Airbag, Chassis, Suspension
Force, Load	Brake pedal, Steering torque, Loading
Vibration	Knocking
Light, Electric wave, Sound	Laser, Microwave, Visible light, IR light, Solar irradiation, Headlight, Voice, Ultrasound
Others	Glow plug, Particle, Rain drop, Humidity, Antenna, Fingerprint, Current

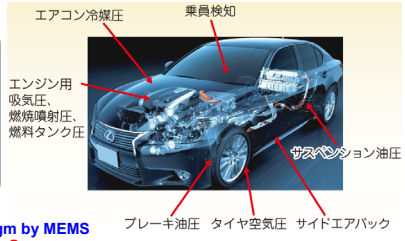
Inner sensor: Pressure, Acceleration, Angular rate (very important to control vehicle)
Outer sensor: Sonar, Rader, Vision (expecting advanced safety)

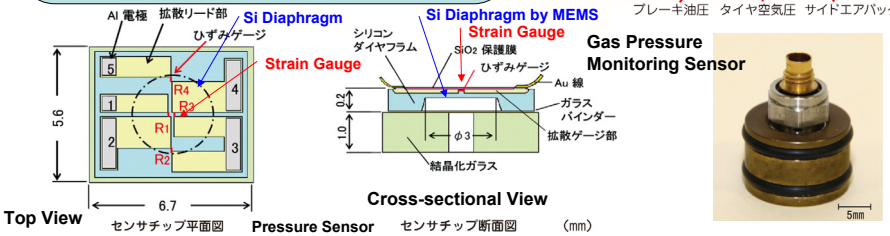
Prize of “One Step on Electro-Technology” from IEE Japan in 2013 (電気の礎)

The Institute of Electrical Engineers of Japan

Piezoresistive Semiconductor Pressure Sensor
Toyota Central R&D Labs., Inc.

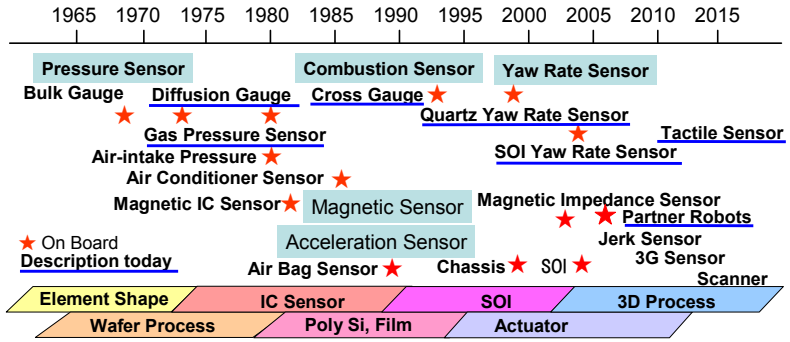
- Si Diaphragm with Semiconductor Strain Gauge with MEMS Technology (1970s)
- Gas Pressure Monitoring Sensor (Toyota Machine Works 1980)
- Intake Pressure Sensor for Automobile (Denso 1981)





from Prize of “One Step on Electro-Technology” of IEE Japan

Automotive Sensor & MEMS Technology



Bulk Micro Machining
Integrated Micro Machining
Surface Micro Machining
SOI Micro Machining
3D Micro Machining

3. Sensors for Automobiles

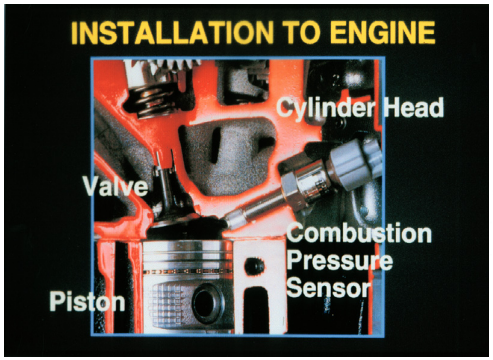
3.1 Combustion Pressure Sensor

Combustion Pressure Sensor

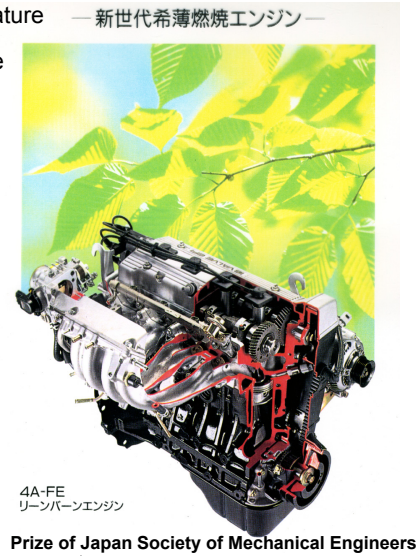
for Low Exhaust Emission

for Low-fuel Consumption

at High Temperature
700-1200degC
at High Pressure
1-2MPa



Lean Burn Engine (TOYOTA)
1993

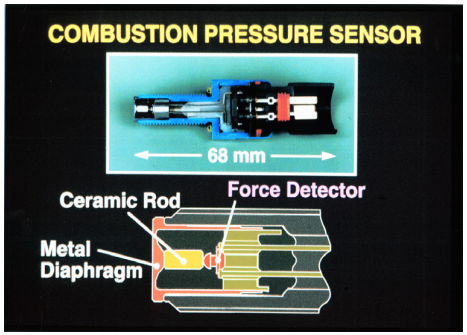


Prize of Japan Society of Mechanical Engineers

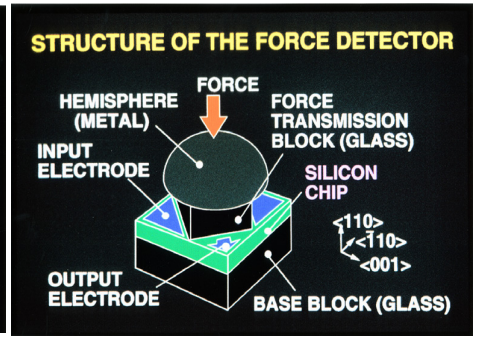
from Y. Nonomura et. al., IMechE (1994)

Combustion Pressure Sensor

Installed on TOYOTA Lean Burn Engine in 1993



Cross Section View

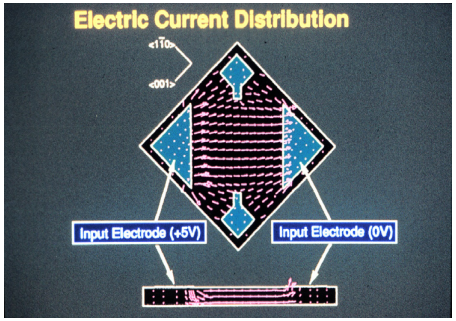


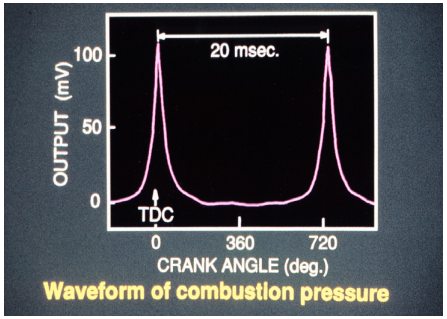
Cross Gauge Type

Piezoresistive effect of Semiconductor single crystal Si

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

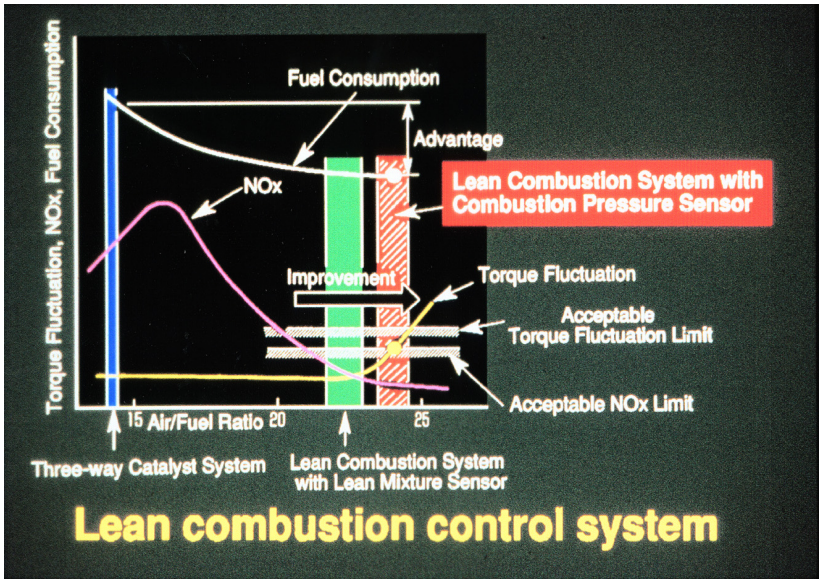
Combustion Pressure Sensor





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

Combustion Pressure Sensor



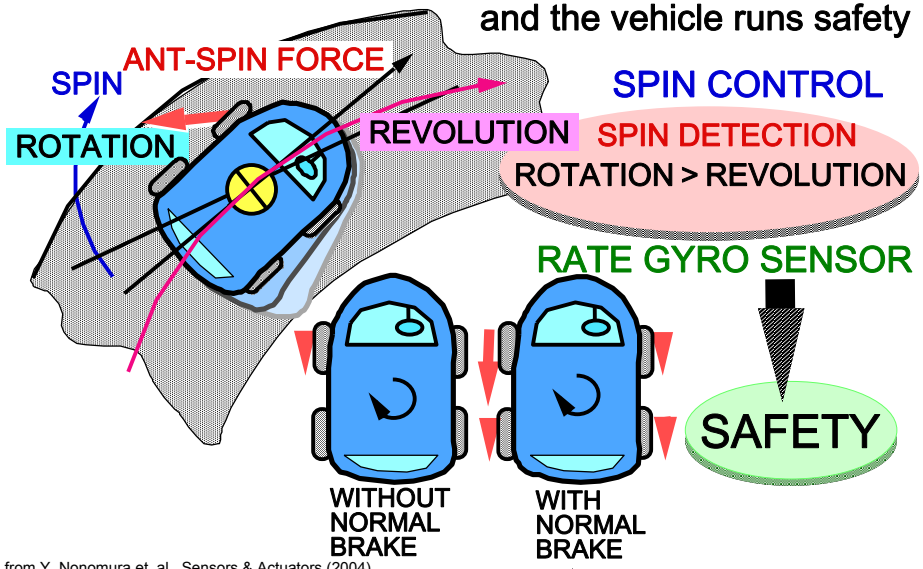
from Y. Nonomura et. al., IMechE (1994)

3. Sensors for Automobiles

3.2 Quartz Yaw Rate Sensor

What is VSC

Generate anti-spin force and the vehicle runs safety

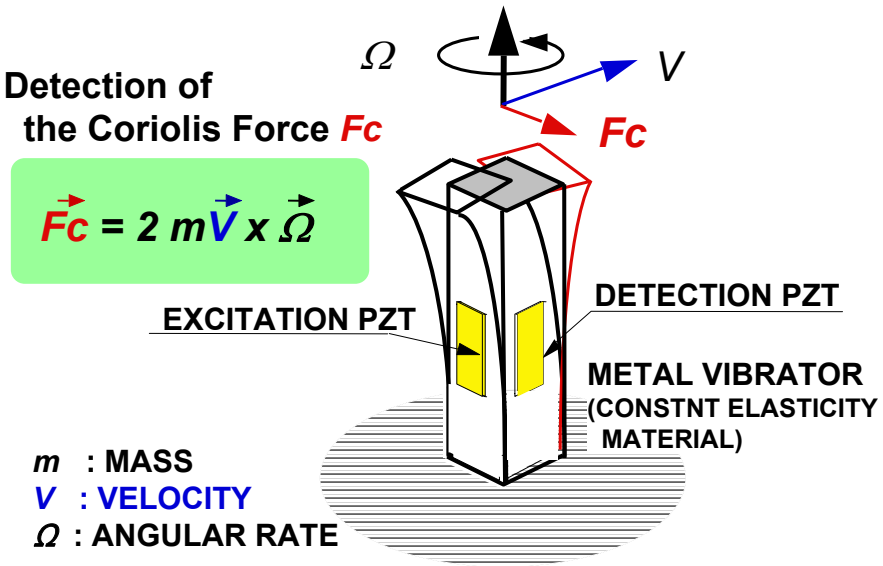


from Y. Nonomura et. al., Sensors & Actuators (2004)

Principle of the Vibration Sensor

Detection of the Coriolis Force *Fc*

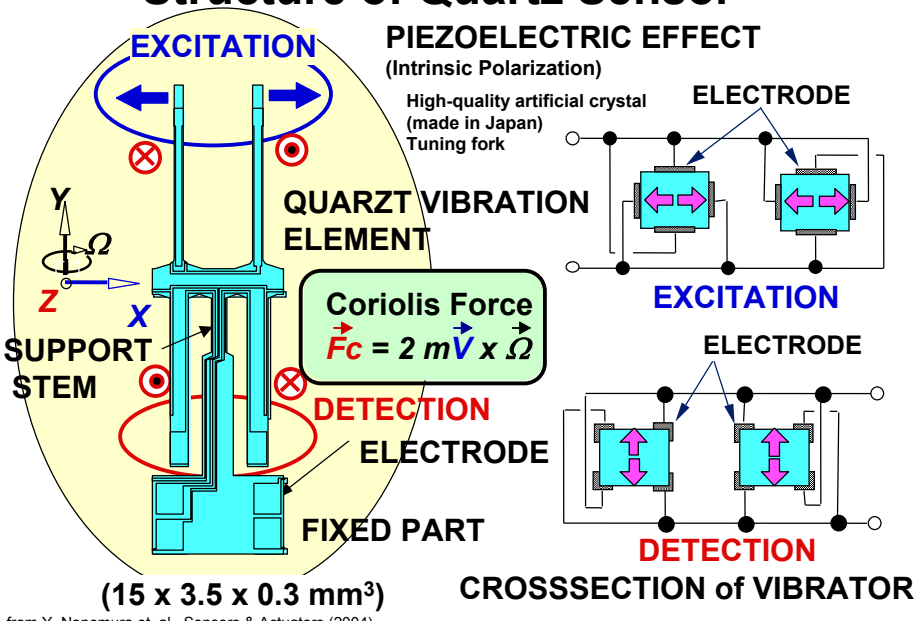
$$\vec{Fc} = 2m\vec{V} \times \vec{\Omega}$$



m : MASS
V : VELOCITY
Ω : ANGULAR RATE

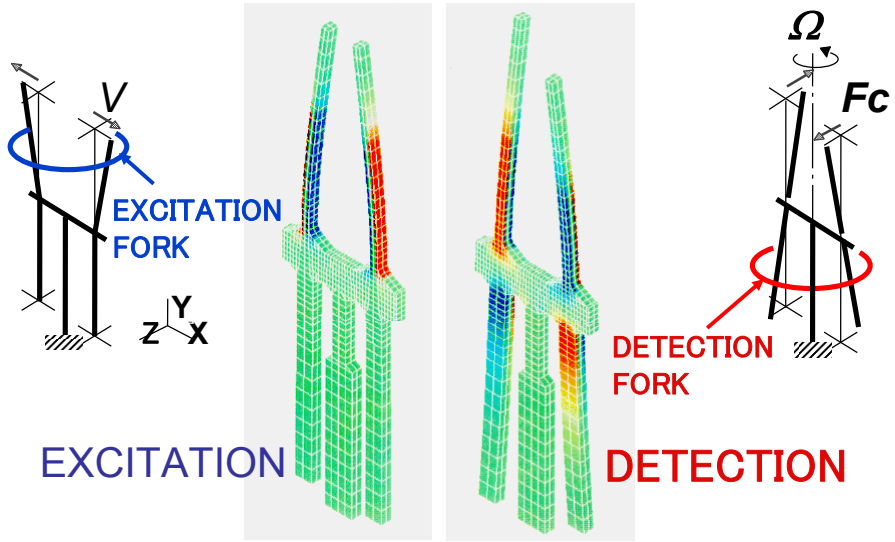
from Y. Nonomura et. al., Sensors & Actuators (2004)

Structure of Quartz Sensor



from Y. Nonomura et. al., Sensors & Actuators (2004)

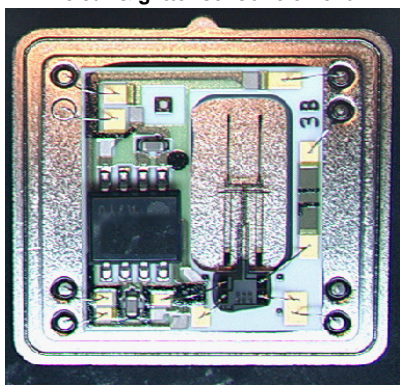
Vibration Mode & Stress Distribution



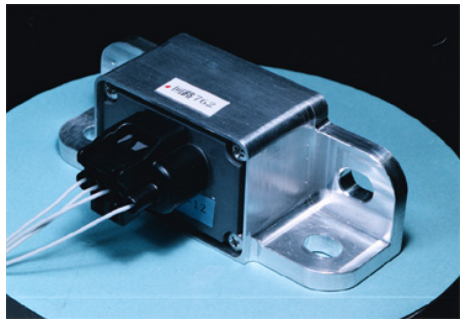
from Y. Nonomura et. al., Sensors & Actuators (2004)

Quartz Yaw Rate Sensor

clear & glitter sensor element



Installed on TOYOTA VSC System in 1998
VSC: Vehicle Stability Control



SENSOR ELEMENT
15 x 3.5 x 0.3 mm^3

IC PACKAGE SIZE
25 x 25 x 5 mm^3

HOUSING
107 x 48 x 37 mm^3
Strong & tough case

from Y. Nonomura et. al., Sensors & Actuators (2004)

3. Sensors for Automobiles
3.3 3-Axis Accelerometer

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

Transducers2011

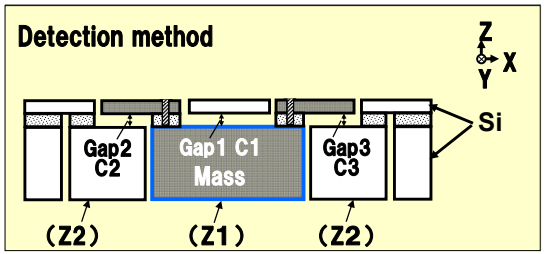
Motivation

- **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.

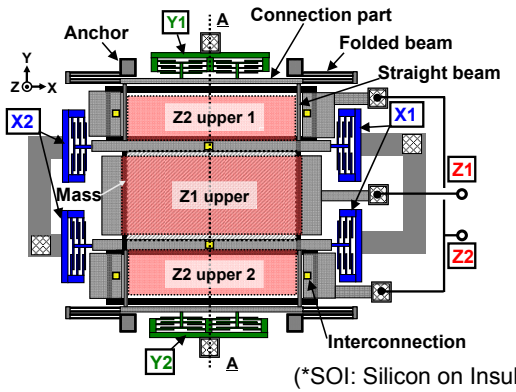
・Gap distances 1-3 are equal by the uniformity of the oxide layer.



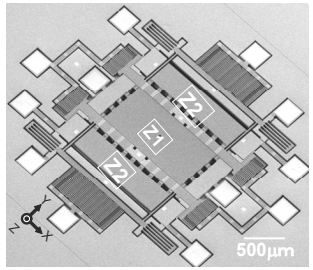
from M. Fujiyoshi, Y. Nonomura, et al. Transducers 2011

Zigzag-Shaped Z-electrode (ZSZ)

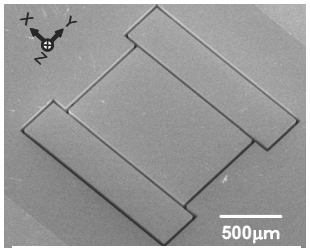
SOI 3-Axis Accelerometer with ZSZ



(*SOI: Silicon on Insulator)



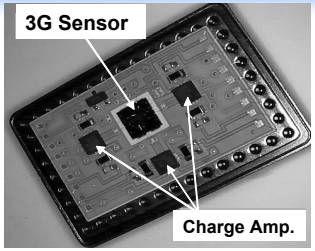
front side



back side

1. SOI* for sensor material
2. All translational motion detection
3. Zigzag-Shaped Z-electrode (ZSZ)

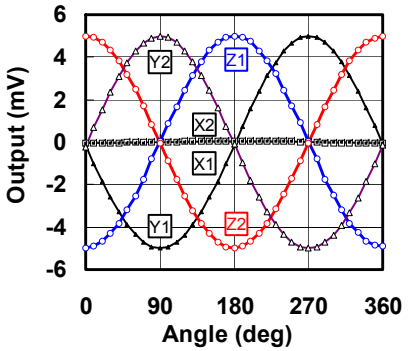
from M. Fujiyoshi, Y. Nonomura, et al. Transducers 2011



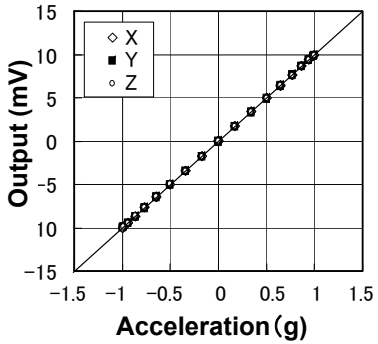
3-Axis Accelerometer

- **Zigzag-Shaped Z-electrode was primarily proposed for 3-axis accelerometer with differential detection.**

before differential



After differential



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

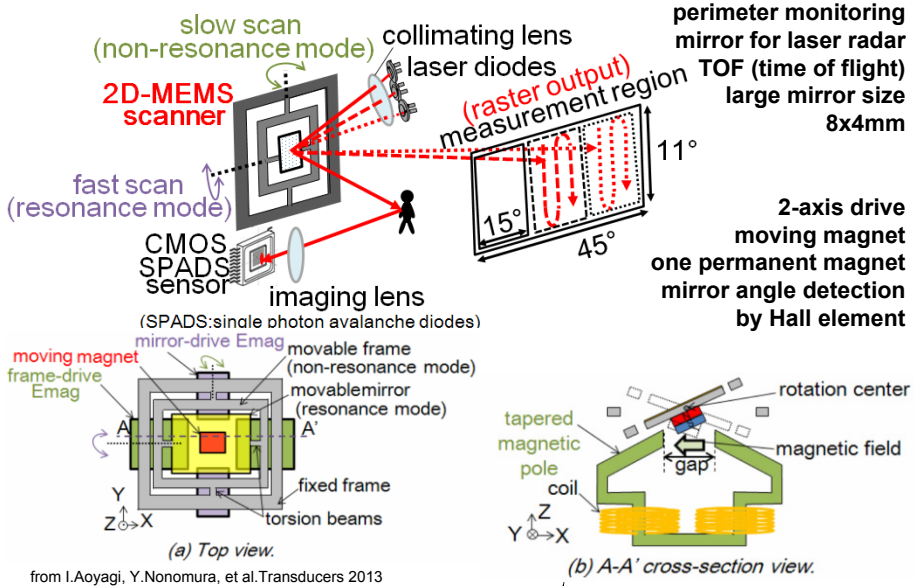
VSC (Vehicle Stability Control)
VDIM (Vehicle Dynamics Integrated Management)

TOYOTA Motor The car with the VSC or VDIM runs safety and smoothly on a slippery road of low μ such as wet, snow, and frozen.

3. Sensors for Automobiles

3.4 Optical MEMS

MEMS Scanner

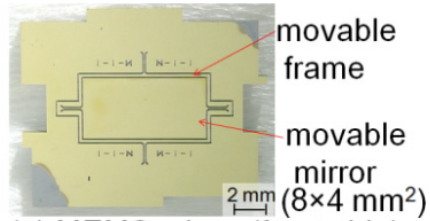


perimeter monitoring
mirror for laser radar
TOF (time of flight)
large mirror size
8x4mm

2-axis drive
moving magnet
one permanent magnet
mirror angle detection
by Hall element

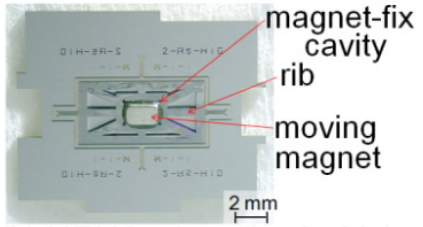
from I.Aoyagi, Y.Nonomura, et al.Transducers 2013

Structure of MEMS Scanner

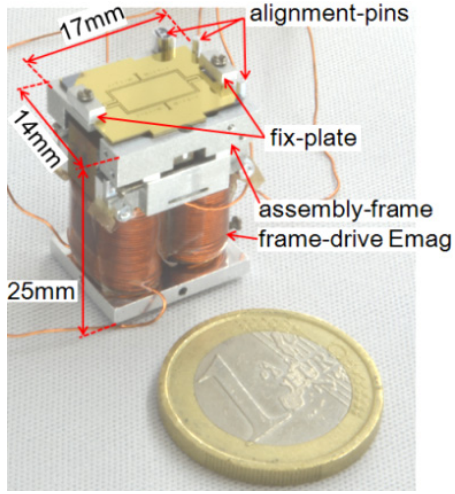


(8×4 mm²)

(a) MEMS mirror (front side).

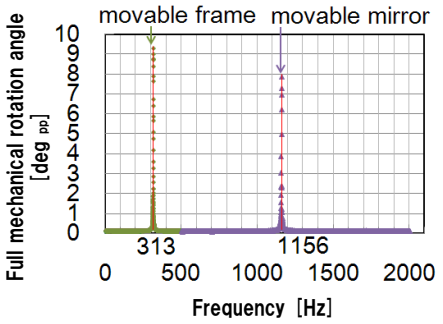


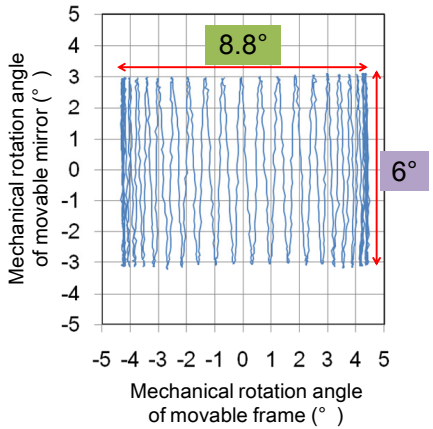
(b) MEMS mirror (back side).



from I.Aoyagi, Y.Nonomura, et al.Transducers 2013

Characteristics of MEMS Scanner





Driving condition
-frame (non-resonance): 30 Hz, 700mA$_{pp}$
-mirror (resonance) : 1.3 kHz, 19mA$_{pp}$

from I.Aoyagi, Y.Nonomura, et al.Transducers 2013

4. Sensors for Robots

4.1 Robot Use of Automotive Sensors

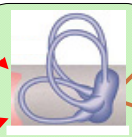
Toyota Group has a dream
to create a new world and style of life with robots as partners.

Role of the Artificial Three Semicircular Canal

Person

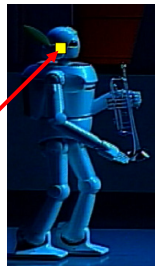
IMU: inertial measurement unit

Walk on stilts
with keeping balance

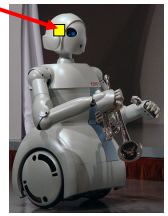


Artificial
Three Semicircular Canal
(Gyro)

Ride on wheel
with keeping balance



Biped-type Robot



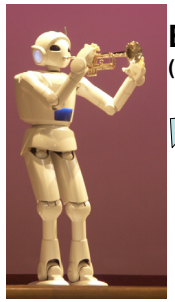
Rolling-type Robot
(Inverted Pendulum)

from Y. Nonomura et. al.,Sensor Symposium, (2006)

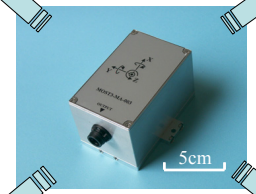
Robots with the Inertial Force Sensing System

Parson Carrier Biped-type Robot

2005
AICHI EXPO

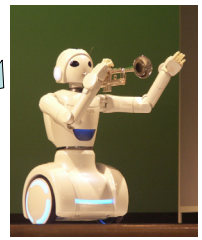


Biped-type Robot
(Plays the Trumpet)



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

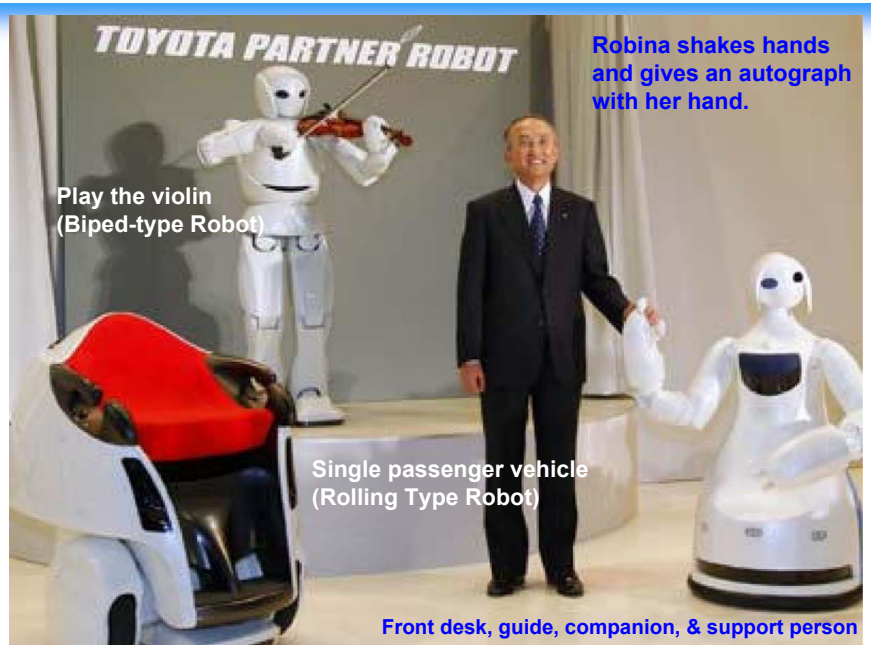
Biped-type Robot with
Wire Drive



Rolling Type
(2 + 1 wheels)
<i-Swing>
2006
Motor Show

Rolling Type (2 wheels) Robot
(Inverted Pendulum)

from Y. Nonomura et. al.,Sensor Symposium, (2006)

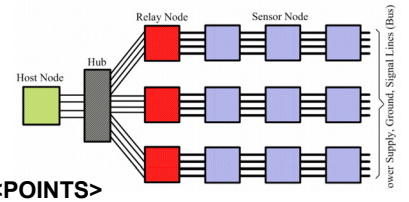


from TOYOTA Motor Corp.

4. Sensors for Robots

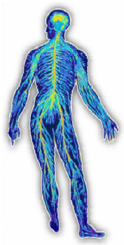
4.2 Tactile Sensor with Nerve Network

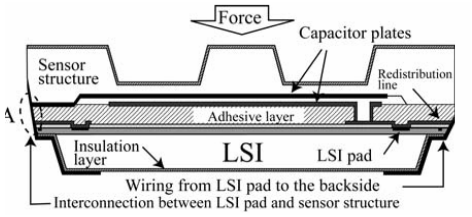
Nerve Net Type Tactile Sensor



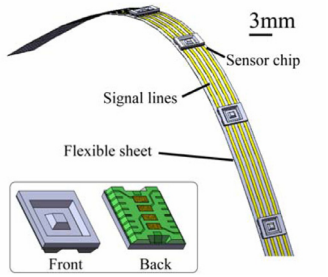
<POINTS>
Serial bus, Event driven against congestion
Sensor chip on signal processor
Signal outputs when force changes
Nerve like relay node

Robina, TOYOTA





Tactile sensor chip

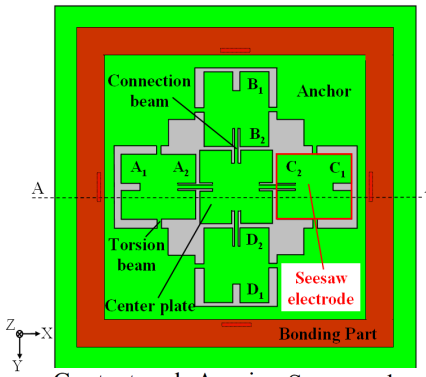


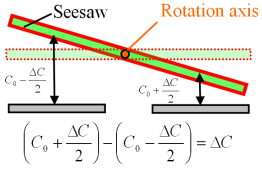
Tactile sensor chip and signal line

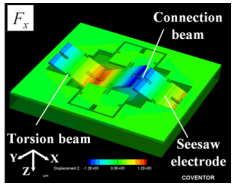
from M. Makihata, Y. Nonomura, et al. Transducers 2011

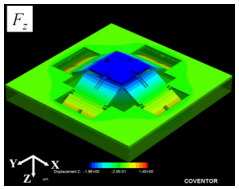
Structure of Tactile Sensor Element

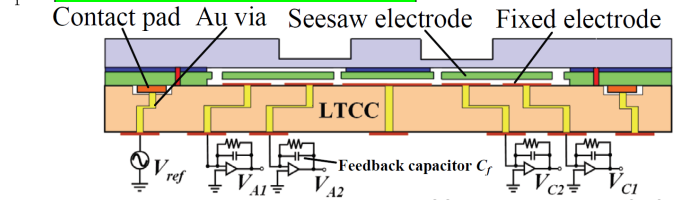
- triaxial force detection with seesaw electrode
- complete differential detection
- electrostatic capacitance detection
- SOI (Silicon on Insulator) substrate stable material
- integrated architecture sensor element and LSI







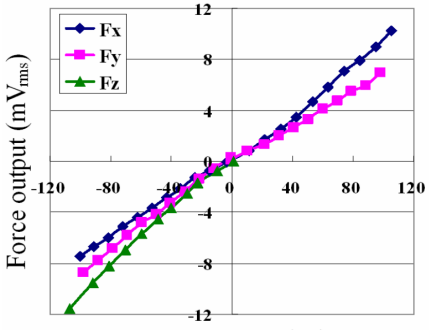




from Y. Hata, Y. Nonomura,et al.,MEMS 2014

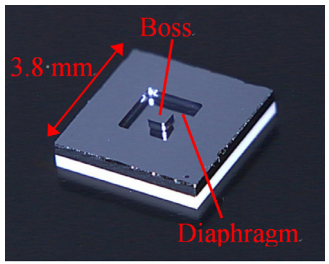
- LTCC (Low Temperature Co-fired Ceramic)

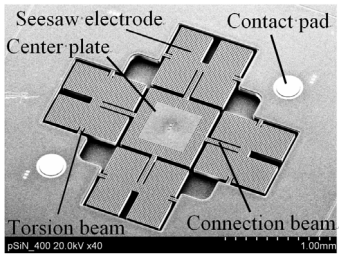
Characteristic of Sensor Element



$$\begin{pmatrix} F_x \\ F_y \\ F_z \\ 0 \end{pmatrix} = \frac{1}{4} \cdot \begin{pmatrix} 2 & 0 & -2 & 0 \\ 0 & 2 & 0 & -2 \\ 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} \Delta V_A \\ \Delta V_B \\ \Delta V_C \\ \Delta V_D \end{pmatrix}$$

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.