Motion Sensor Technology and Applications Overview

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Motion Sensors

Six-Axis Motion Device

MotionApps™

APIs
Calibration Algorithms

DMP
Sensor Fusion

Gyro
Accel
Pressure Sensor
Compass

Sensor + Processor Core

InvenSense
## Motion Sensor Applications

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Used For</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyroscope</td>
<td>Rotation Rate</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>Linear Acceleration</td>
</tr>
<tr>
<td>Pressure Sensor</td>
<td>Relative Elevation</td>
</tr>
<tr>
<td>Compass</td>
<td>Direction</td>
</tr>
</tbody>
</table>

- **Auto & Industrial**
- **Virtual Reality**
- **Location & Activity Tracking**
- **Wearable**
- **Image Stabilization**
- **Appliances**
- **Sports & Fitness**
- **Smart TV**
- **Tablets**
- **Toys**
- **Smart Phones**
- **Gaming**
- **Imaging**
Application: Health/Fitness Tracker

Activity/Context
Steps, Activity, Sleep

Vital Signs Monitoring
Motion Artifact Correction

Sensor Assisted GNSS
Running: Speed/Distance/Route

Gyro
Accel
Compass

Barometer Support
Floors Climbed

Pressure Sensor

OEM
Health/Fitness
Cloud

Health Services
Application: Navigation

- **Outdoor Navigation:**
  - GPS + Compass is common (<10m accuracy)
  - 9-axis helps in urban canyon environments

- **Indoor Navigation:**
  - No GPS, WiFi triangulation for 10-30m accuracy
  - 9-axis provides 1-10 meter accuracy
  - Pressure Sensor: Which floor?
High performance Gyroscope is important for AR/VR
- Key specs: Gyro Noise, Gyro Offset, and Gyro Sensitivity
- **User Experience:** Orientation stays fixed to the real world so that Pokeman stays in the same location even after user hand jitter
- Mobile gets hot because GPS, AP/Graphics, Display and Gyro on 100%.
- Stable gyroscope performance over temperature is critical
- **User Experience:** Pokeman won’t drift over camera scene as mobile temp increases.
Gyroscope
MEMS Gyroscopes use Coriolis Effect to measure Angular Rate

- Mass \( m \) is moving with velocity \( \mathbf{v} \) and Angular velocity \( \Omega \) is applied to \( m \)
- Resulting force \( \mathbf{F} = -2m\Omega \times \mathbf{v} \) (called Coriolis force) causes object displacement
- \( \Omega \) can be calculated from the measured displacement
- Displacement is measured via capacitive change between the moving mass \( m \) and fixed structure
- In practice 2 masses moving in opposite directions are used
  - Resulting Coriolis forces are in opposite directions
  - Differential capacitance between the two masses used to measure \( \Omega \)
  - If linear force is applied the two masses move in the same direction and differential capacitance is zero—makes gyroscope robust to linear acceleration
MEMS Gyroscope 3-Axis

InvenSense MEMS Gyroscopes

— X-axis and Y-axis Gyroscopes: Masses move up and down (perpendicular to package plane) resulting in in-plane Coriolis forces for X and Y rotation
— X-axis and Y-axis Gyroscope are basically the same structure mounted 90° from each other as shown in Figure B
— Z-axis Gyroscope: Masses move in-plane as shown in Figure C
Key Gyroscope Parameters

• Sensitivity
  — Gyroscope output change when subject to 1 dps or deg/sec
  — ADC word of 16-bits, number of possible output levels $2^{16}$
  — With a Full Scale Range (FSR) ±250 °/sec, sensitivity scale factor is $2^{16}/(±250) = 131$ levels (or LSBs)/dps

• Bias & Variation over Temperature
  — Ideally at zero at rest, but in reality is non-zero, affected by temperature
  — Called Zero-Rate Output (ZRO) and expressed in deg/sec (dps)

• Noise
  • Random low rate change at rest due to-
    • Mechanical non-linearity
    • White noise from CMOS
  • Measured rate (density) & RMS
  • Seen as drift when integrated over time

ZRO or Bias (dashed red line) = 0.15dps
Accelerometer
MEMS Accelerometer Basics

MEMS Accelerometer

- Suspended proof mass \( m \) reacts to acceleration in its axis of orientation by moving.
- Movement changes capacitance \( C \) between the mass and its sense electronics.
- Capacitance converted to voltage & digitized to provide a measure of acceleration.
Key Accelerometer Parameters

• Sensitivity
  — Accelerometer output change when subject to 1g
  — ADC word of 16-bits, number of possible output levels $2^{16}$
  — With a Full Scale Range (FSR) ±2g, sensitivity scale factor is
    $2^{16}/(±2) = 16,384$ levels (or LSBs)/g

• Bias & Variation over Temperature
  — Ideally at zero at rest, but in reality is non-zero, affected by temperature
  — Called Zero-G Output (ZGO) and expressed in mg
  — Ideal output for X, Y, Zaccel at zero is 0, 0, 1g

• Noise
  • Random low rate change at rest due to-
    • Mechanical non-linearity
    • White noise from CMOS
  • Measured rate (density) & RMS
  • Seen as drift when integrated over time
Compass
• Hall Effect
  - Occurs when a magnetic field is applied transverse to flowing current
  - Magnetic field deflects the charges that make up the current, inducing a voltage (called Hall Voltage)
  - Hall voltage can be measured to determine the strength of magnetic field transverse to the current
  - Use multiple sensors oriented in different directions to measure total magnetic field
Features of AKM's e-compass

• Features of device
  – Using Hall elements as magnetic sensor
    • Wide range of magnetic sensing: ±4900μT
    • Excellent linearity
    • Reset operation is not necessary against exposure of strong magnetic field.
  – Si monolithic structure
    • 3-axis magnetic sensor and ASIC are integrated into one chip Si-monolithic IC
    • Small, thin and simple structure
    • Higher-order orthogonal 3-axis sensing of magnetic field

Having above features, AKM's e-compass is most suitable for various mobile devices.
Pressure Sensor
Pressure Sensor Use Cases

**Navigation**
- Floor Change
- Absolute Height
- Indoor Navigation

**Fitness**
- Calorie Counter
- Cumulative Height
- Stair Step Count

**Context**
- Drop Detection
- Guestures
- In-Water Detect
The barometer measures change in pressure, not altitude.
Composed of a diaphragm, exposed to the external environment.
Underneath the diaphragm are electrodes on the CMOS.
Diaphragm deflection is a function of the external pressure.
CMOS electrodes measure the change in vertical gap (capacitance) due to deflection of the diaphragm.

**Absolute Accuracy:**
- The difference in measured pressure from the actual pressure

**Relative Accuracy:**
- Relative difference between absolute pressure measurements at two different locations, a measurement of pressure change
  - Used to track altitude change for tracking vertical motion
Strain measurement with **piezoresistors**  

Measurement of **Capacitance**

Advantages of capacitive sensors over current state of the art resistive ones:

- Low power consumption: No current flow when measuring capacitance
- Best temperature stability: Piezoresistors are highly sensitive to temperature
- Low noise: Thermal noise of piezoresistors fundamentally limits repeatability at output
- High accuracy: Capacitive principle more sensitive to pressure changes
Pressure Change: Stair Step Detection

InvenSense Pressure Sensor tracking steps up and down

Correctly classified: 94%
Motion Sensor Devices
MotionTracking Solution

- Sensors calibrated as a complete system for best performance
- Optimized MotionFusion software for guaranteed performance
- Smallest board space, low power
- Less components and fewer vendors to qualify
- Higher system reliability
## 6-Axis and 9-Axis Products

<table>
<thead>
<tr>
<th>Device</th>
<th>Highlights</th>
<th>Mobile</th>
<th>Sports</th>
<th>AR/VR</th>
<th>Wear</th>
<th>Image</th>
<th>IoT</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICM-20648</td>
<td>4K FIFO + DMP</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
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<tr>
<td>ICM-20649</td>
<td>±4000dps, ±32g</td>
<td></td>
<td>✓</td>
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<tr>
<td>ICM-20948</td>
<td>9-axis, ±2Kdps, ±16g</td>
<td></td>
<td></td>
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<td>✓</td>
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<tr>
<td>ICM-20600/2</td>
<td>2.5x3mm; 3x3mm</td>
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<td></td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
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<tr>
<td>ICM-20603</td>
<td>3x3mm w/ HMD/VR SW</td>
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<td></td>
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<td>✓</td>
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<tr>
<td>ICM-20690</td>
<td>Dual Interface; Wide FSR</td>
<td>✓</td>
<td></td>
<td></td>
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<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
Motion Sensors Output

Sensor Kinetics

Accelerometer Sensor

X = +0.07 m/s²
Y = -0.00 m/s²
Z = -9.79 m/s²

Set Rate: 30Hz  Measured Rate: 30Hz

Gyroscope Sensor

X = -0.01 rad/s
Y = +0.00 rad/s
Z = +0.00 rad/s

Set Rate: 30Hz  Measured Rate: 30Hz

Magnetometer Sensor

X = -72.9 µT
Y = +5.4 µT
Z = -53.4 µT

Measured Rate:
Thank You