CS7351 传感系统原理与设计
Principles and Design of Sensing Systems

Sensors – Inertial Measurement Unit (惯性传感器)

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2025年秋季

Paper Presentation Schedule

Name	Topic	Title
朱腾杰		
吴媚		
谢婧		
付晨龙		
何弈拓		
张卜元		
RICHARD DANIEL LIU		
邱宇豪		
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郑颜昊		
Distribution of topics: IMUx2, Acoustic, Camera, Securityx2, Navigation, Magnetic, Miscx2		

Presentation requirement:

1. Please plan a **15-20 min presentation** and a **5 min Q&A**
2. The presentation **should include**:
   - Motivation, related works, technical challenges, solution, evaluation, and future works
3. The presentation should be prepared English but can be presented in either Chinese or English

Paper list-CS7351-2025
https://docs.qq.com/sheet/DUnZaaVh5QWJVSUNm?tab=BB08J2

Please go through the paper list and put your selection here. Please complete the form **by October 9th.**

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- Practicing artifact evaluation for your future works
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Artifact Evaluated NDSS Available

DualStrike: Accurate, Real-time Eavesdropping and Injection of Keystrokes on Commodity Keyboards

Xiaomeng Chen[†], Jike Wang[†], Zhenyu Chen[†], Qi Alfred Chen[‡], Xinbing Wang[†], Dongyao Chen[†✉]
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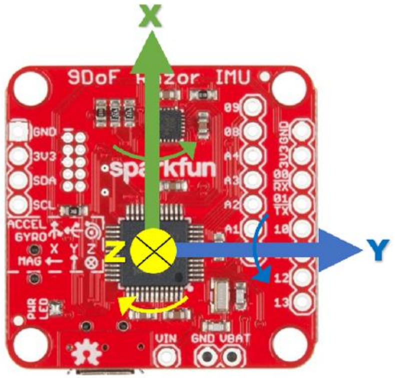
Quick Recap: How to Design Your Sensing Application?

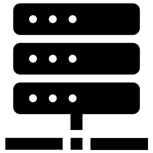
- Step 1: What problem you want to solve?

- Step 2: Examine the 4 key design principles

4 Key Principles for Designing Sensing Systems



Sensing Modalities



Computation

Power and Energy

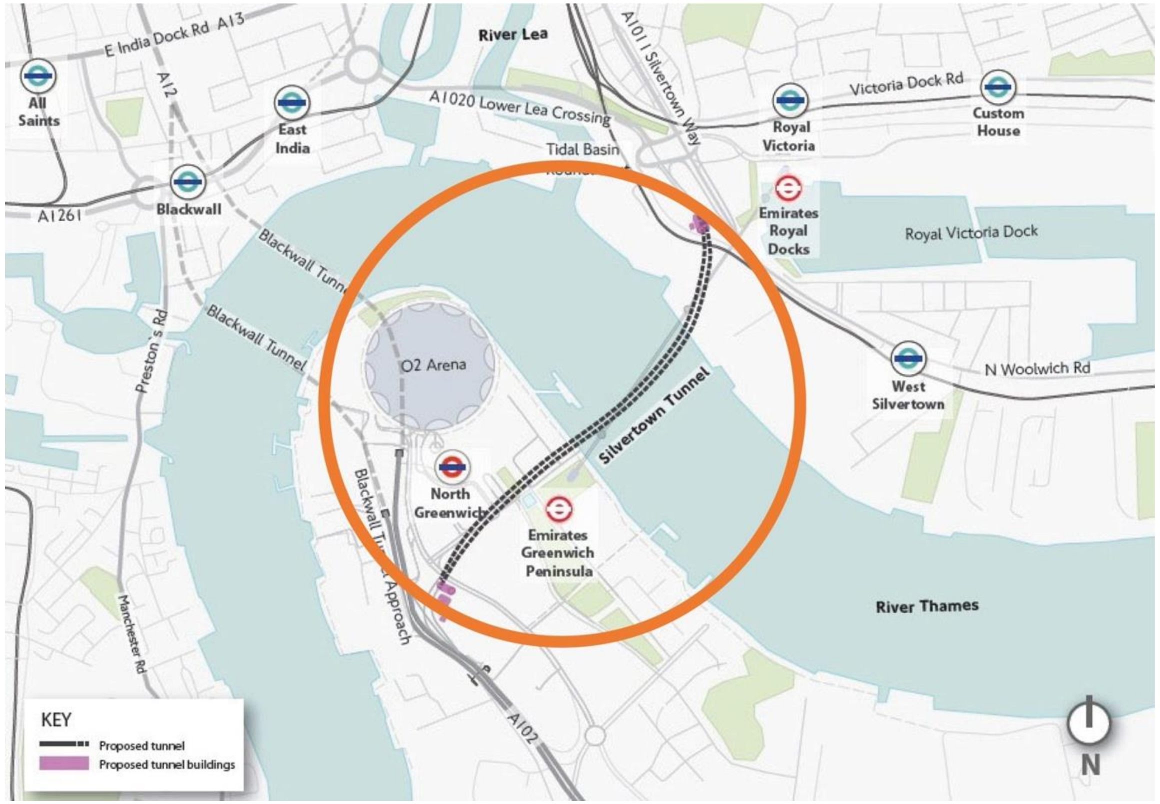
Connectivity

Outline

- An Introduction of IMU
- IMU Error Model
- IMU Calibration

Example Application of IMU: Inertial Navigation

- Navigate in tunnels



- How to navigate when you cannot receive satellite data?

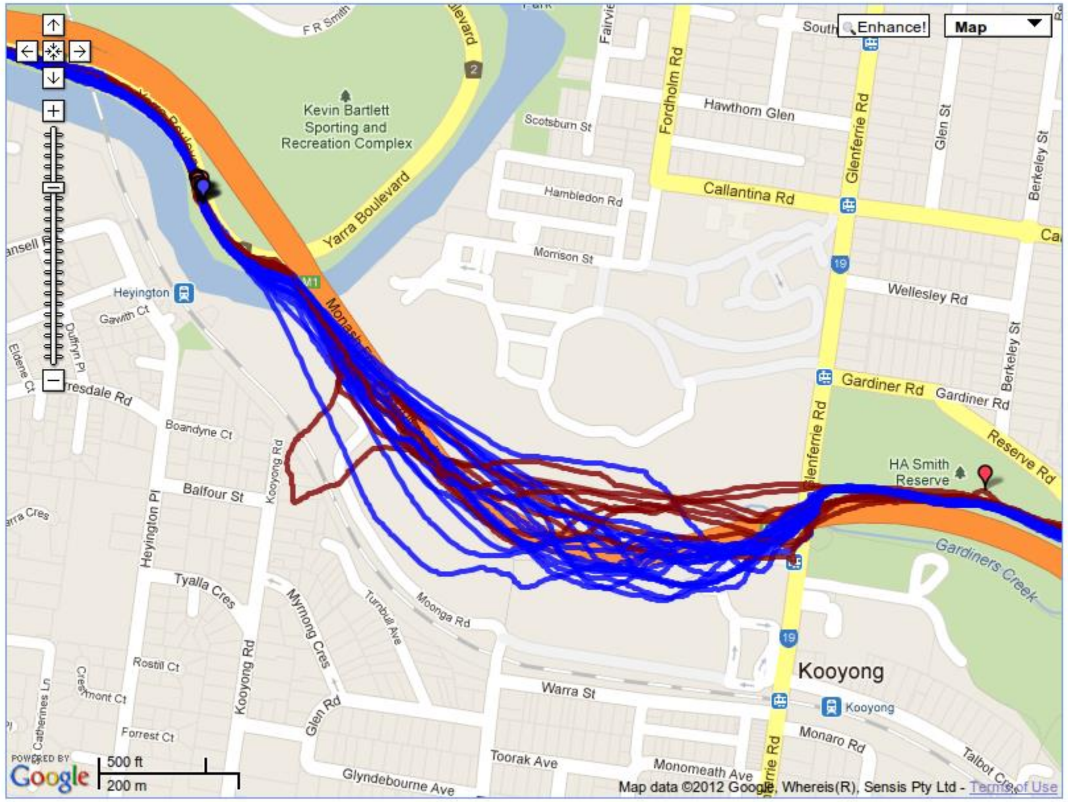
Example Application of IMU: Mitigate Urban Canyon Problem

GPS only

GPS+INS

- Key idea: integrate acceleration data over time to derive location

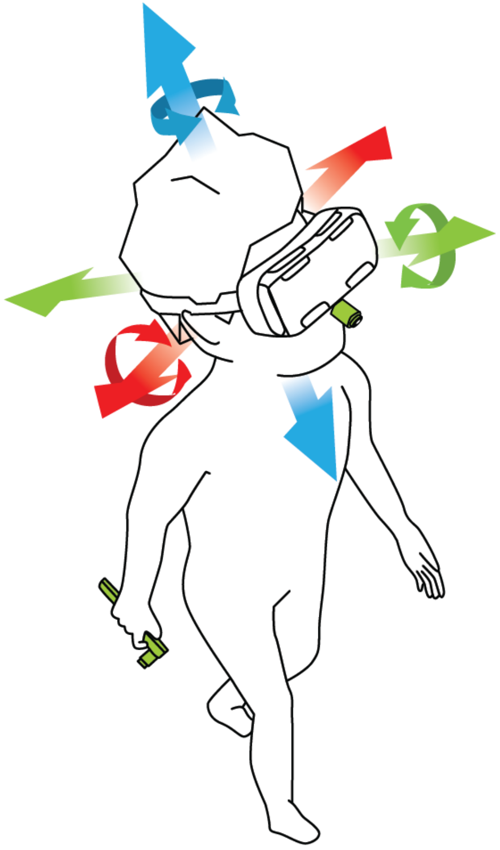
Is Inertial Navigation Accurate?



- How to analyze the error?

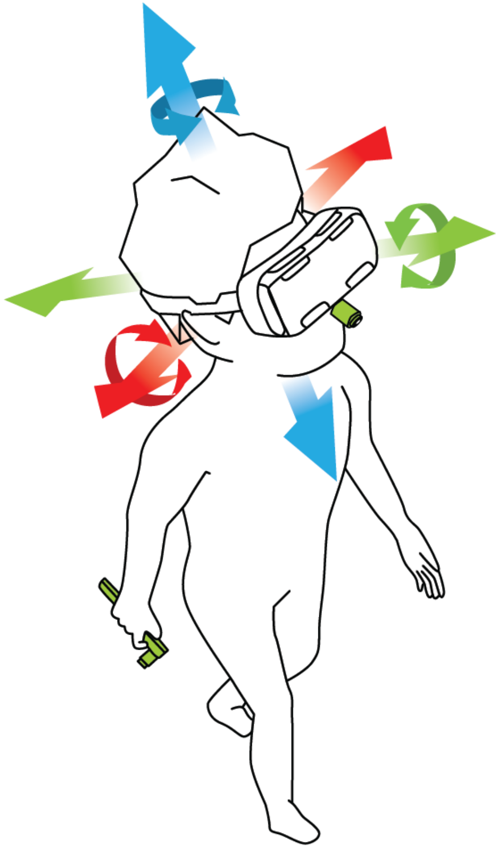
Example Application of IMU: Headset Tracking

- **Goal:** track location and orientation of head or other device
- Coordinates: Six degrees of freedom:
  - Cartesian frame of reference (x,y,z)
  - Rotations represented by Euler angles (yaw, pitch, roll)



Example Application of IMU: Headset Tracking

- **Gyroscope** measures angular velocity ω in degrees/s
- **Accelerometer** measures linear acceleration a in m/s^2
- **Magnetometer** measures magnetic field strength m in μT (micro-Teslas).



Where are IMUs Used Today?

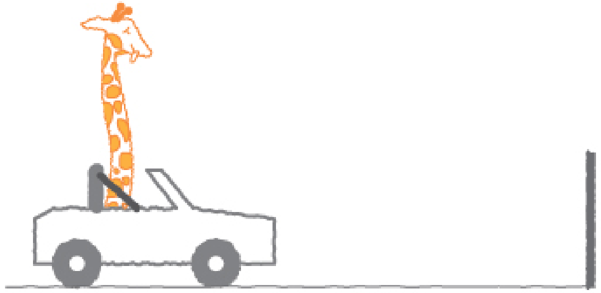
Outline

- An Introduction of IMU
- IMU Error Model
- IMU Calibration

Why it is Called Inertial Measurement Unit?

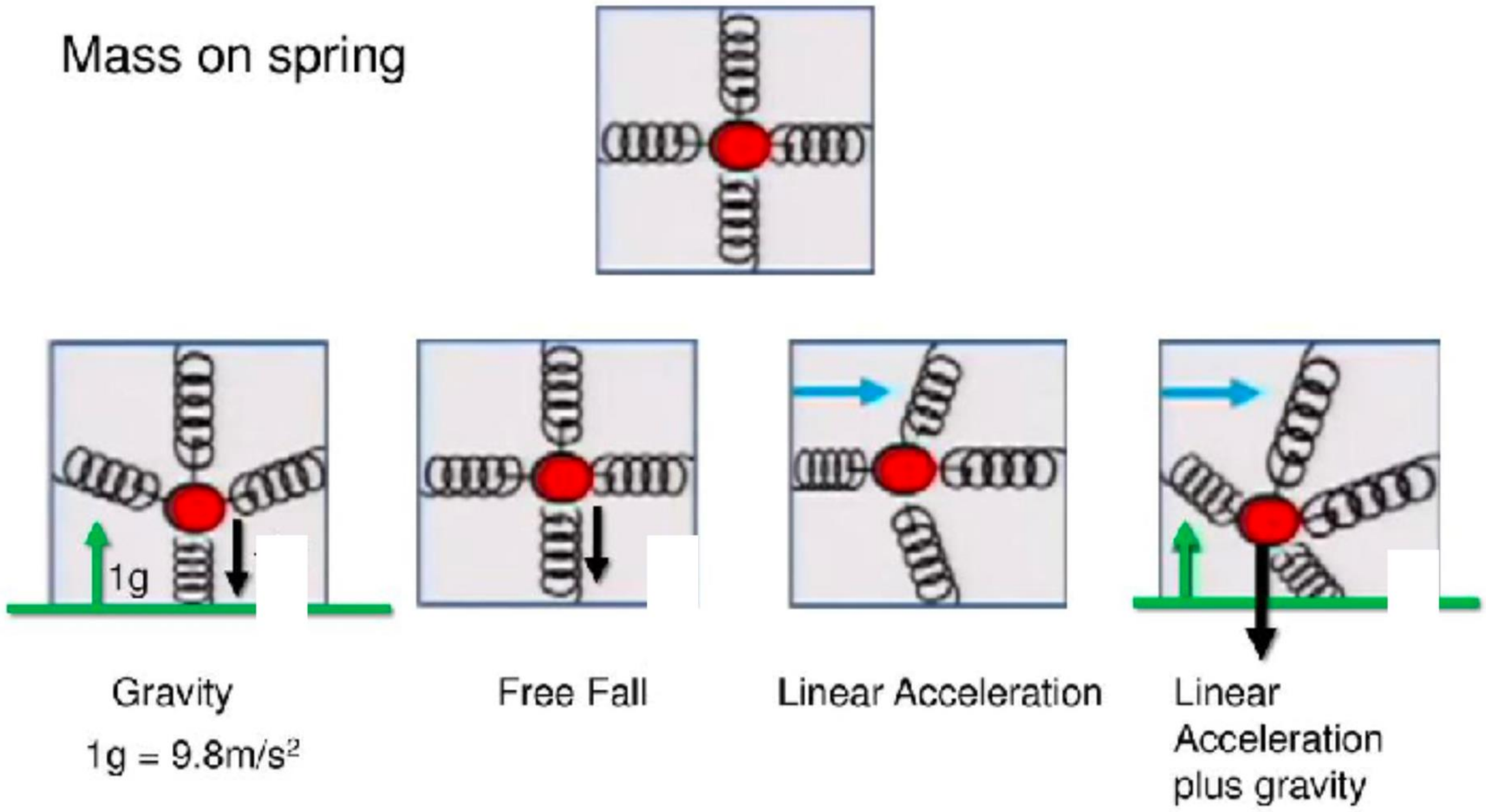
- What is inertia?
  - It means an object will continue its current motion until some force causes its speed or direction to change.
- Rotation inertia
  - A rotating rigid body maintains its state of uniform rotational motion.

Inertia Example #1: Why you need to wear a seatbelt (especially if you are a giraffe)

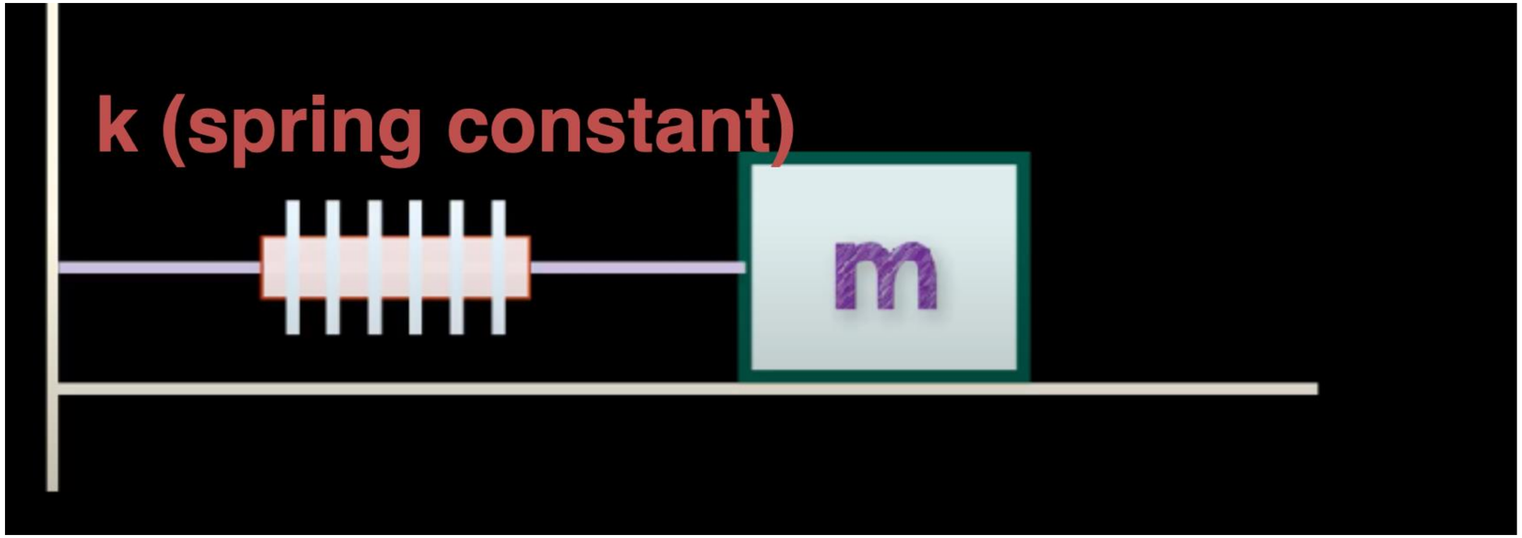


How Accelerometer Work?

- It measures acceleration



How Accelerometer Work



Hooke's Law

$$F = kx$$

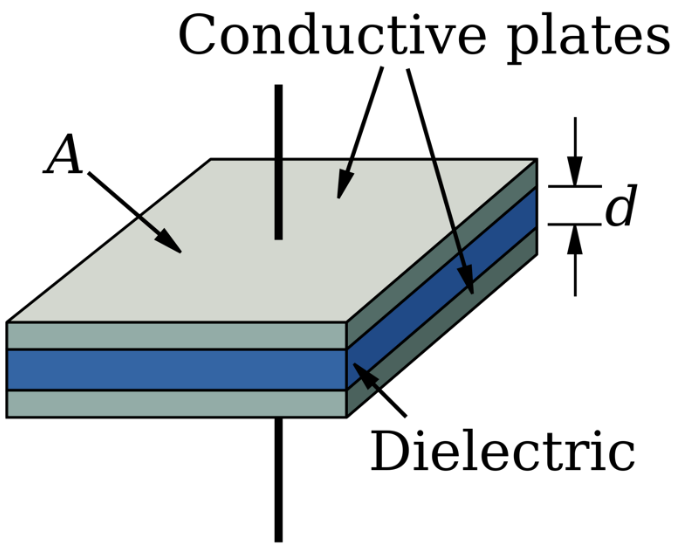
Newton's Law

$$F = ma$$

$$=> a = \frac{k}{m}x$$

- How to measure x?

How Accelerometer Work



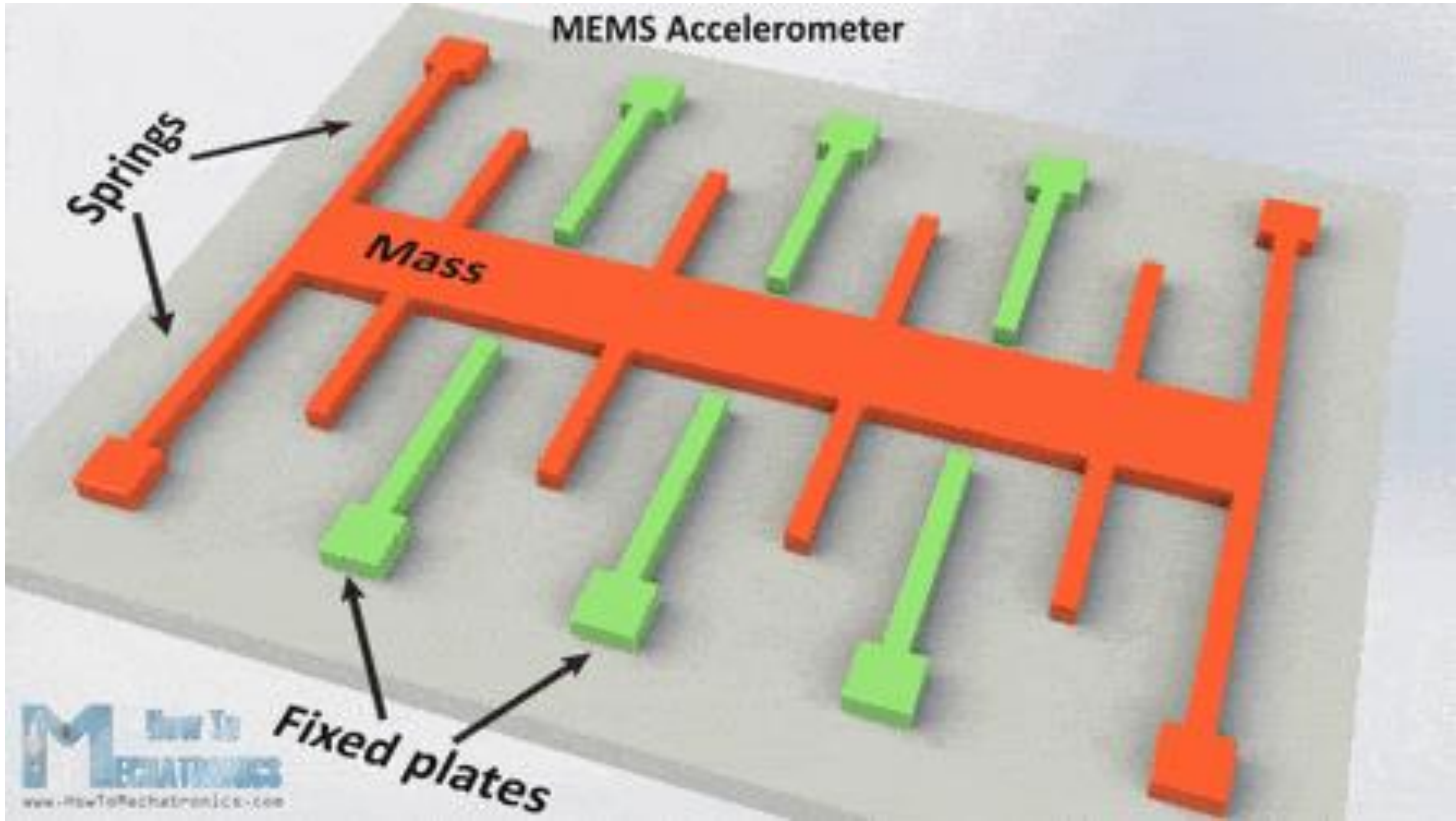
$$C = \frac{\varepsilon A}{d}$$

- C: capacitance
- A: area
- ε : permittivity
- d: distance

We can measure the varying displacement to measure acceleration!

How to Measure the Changing Distance?

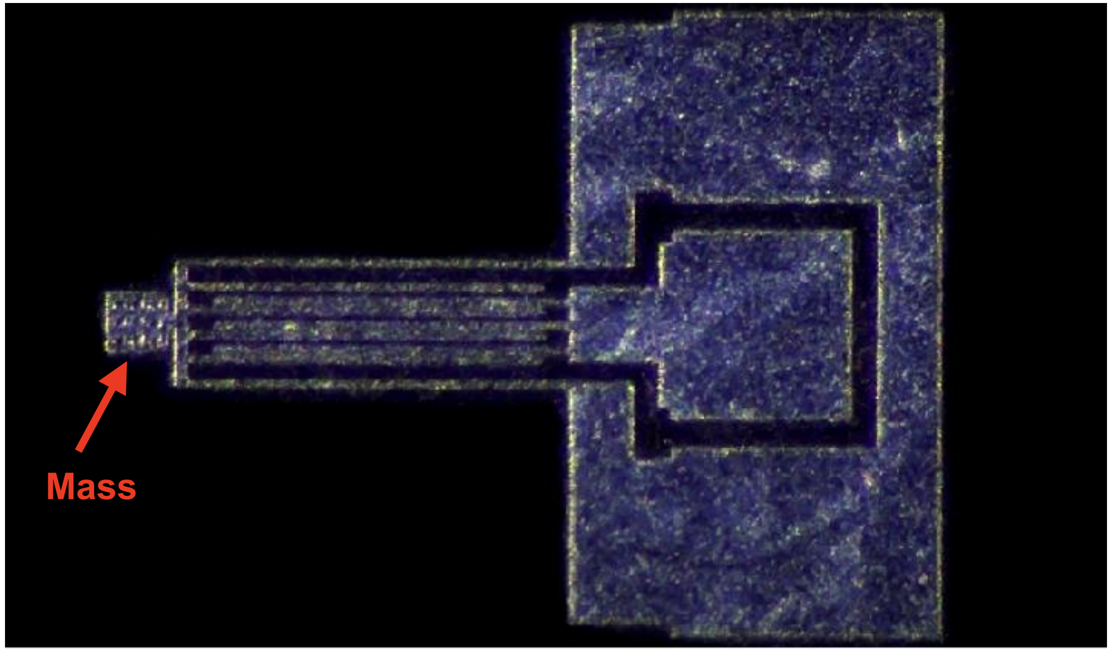
- Most common approach is to use MEMS (Micro electro-mechanical systems)

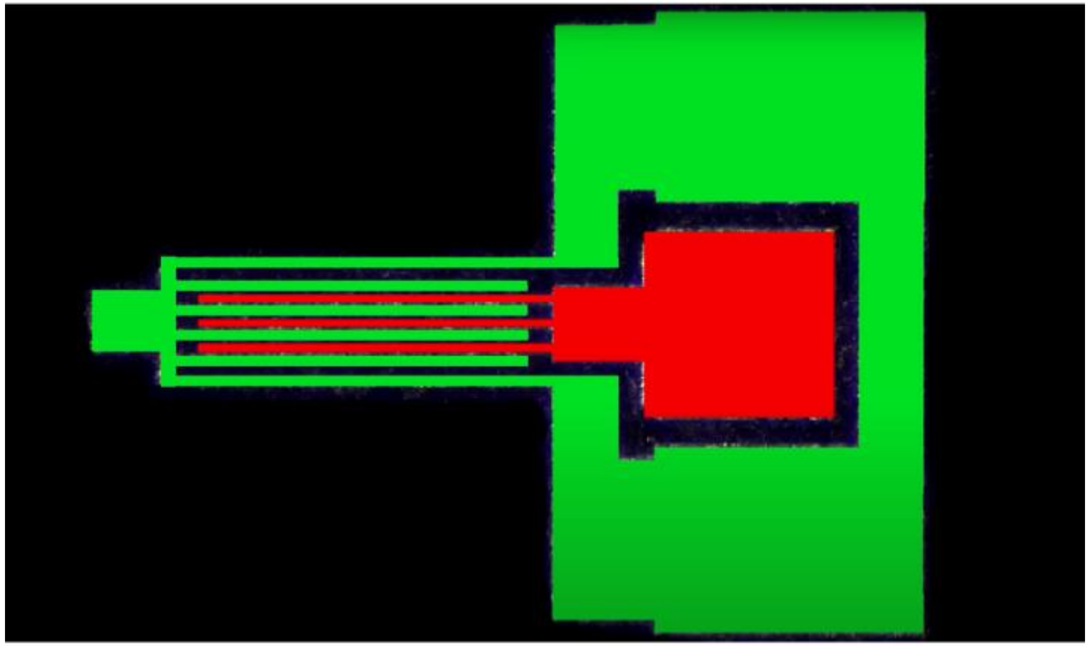


How to Measure the Changing Distance?

- Most common approach is to use MEMS (Micro electro-mechanical systems)

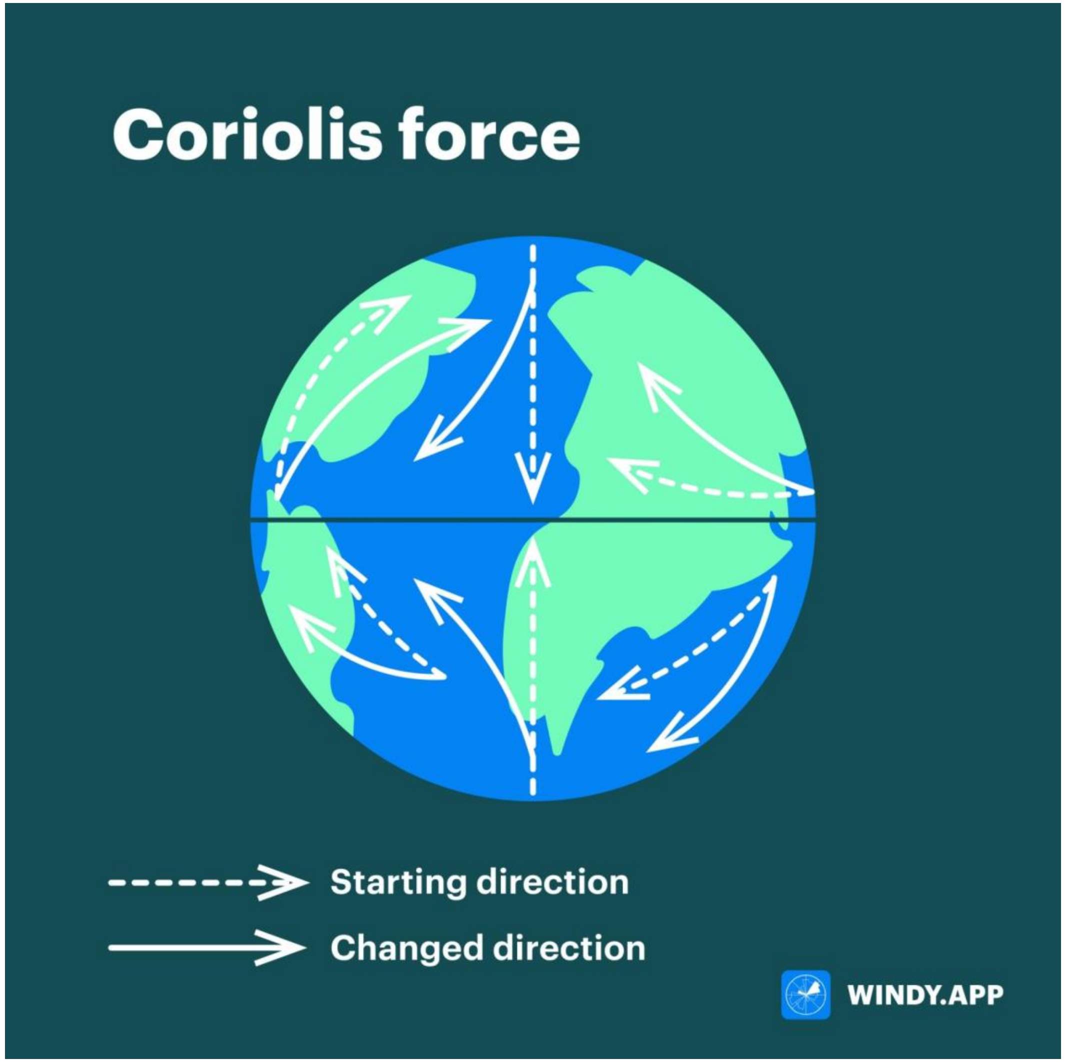
MEMS Accelerometer





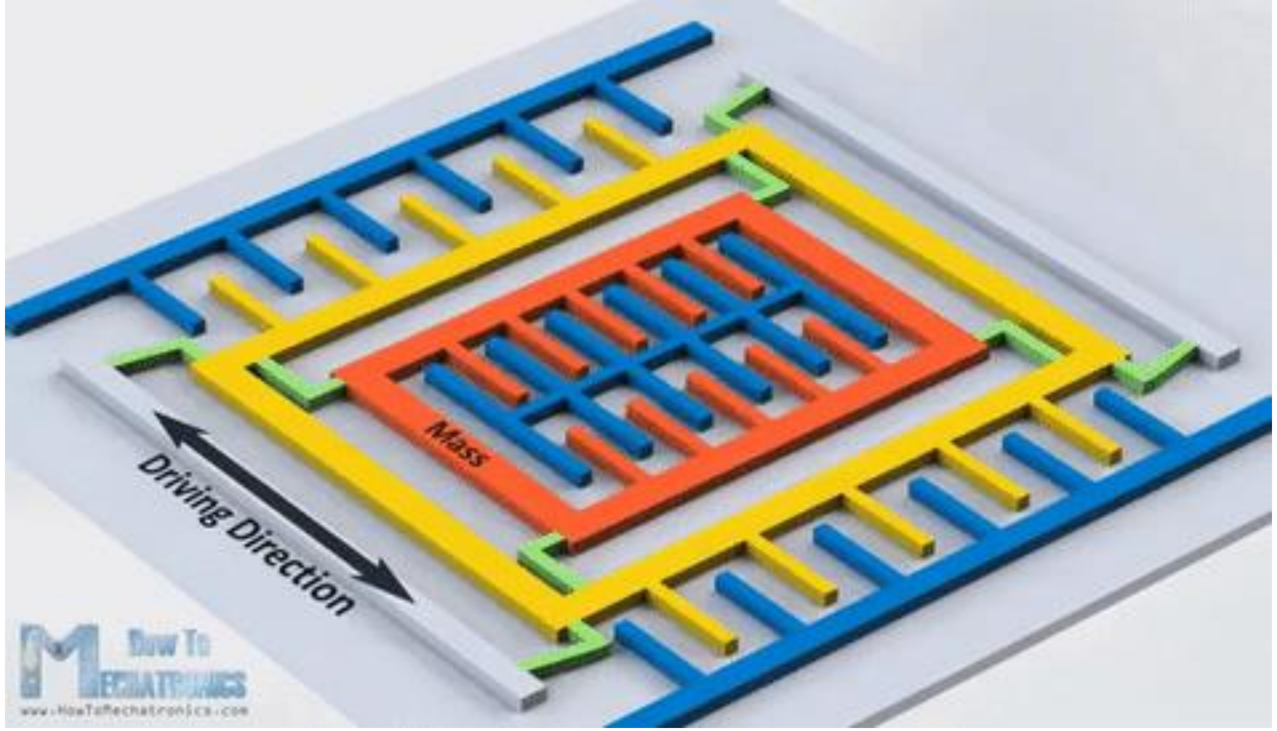
How Gyroscope Work

- It measures angular speed (rad/s)
- Foundation: Coriolis Effect



How Gyroscope Work

- It measures angular speed (rad/s)
- Foundation: Coriolis Effect + MEMS

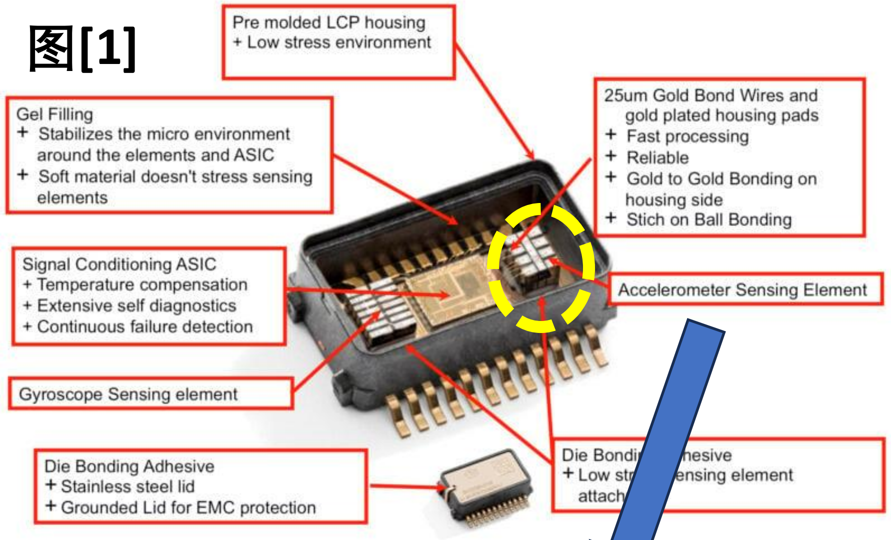


IMU原理&&结构

Accelerometer sensing element

inside the chip

图[1]

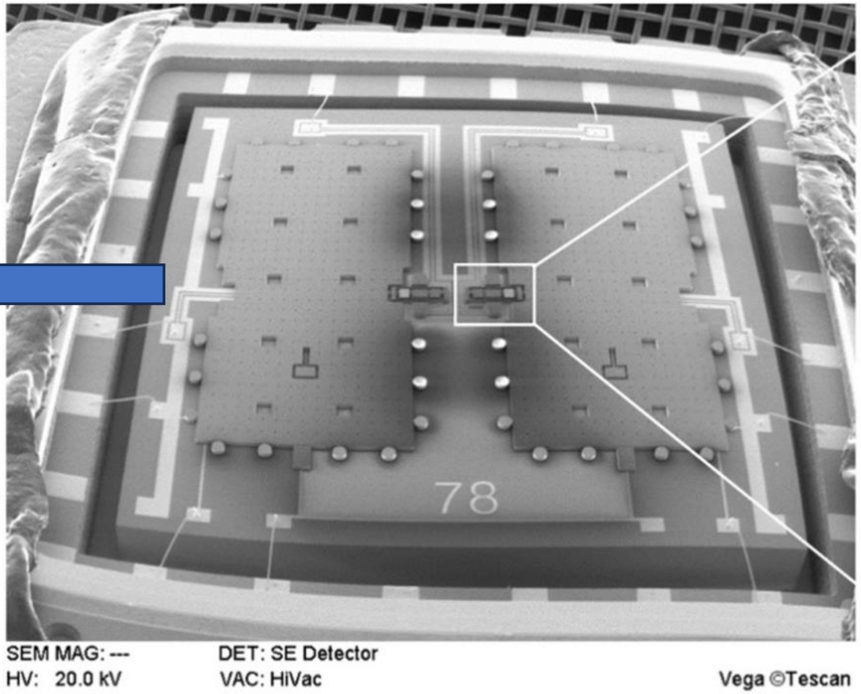


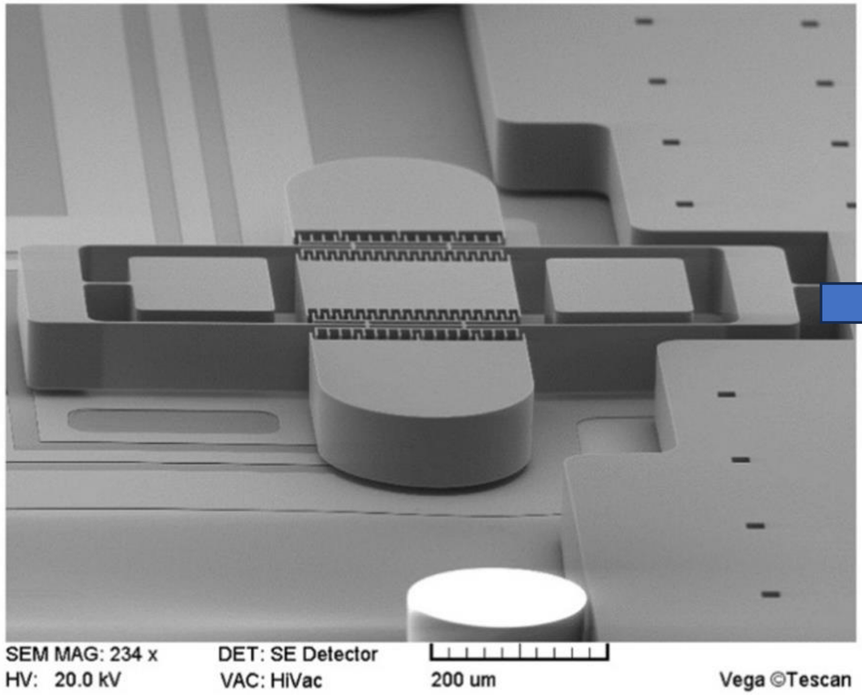
左图：Accelerometer sensing element

扫描电子显微镜（SEM）图像

图[2]

这一整块区域就称为MEMS DIE





Capacitive accelerometer

核心resonator

Capacitive accelerometer 核心resonator结构

图[1]

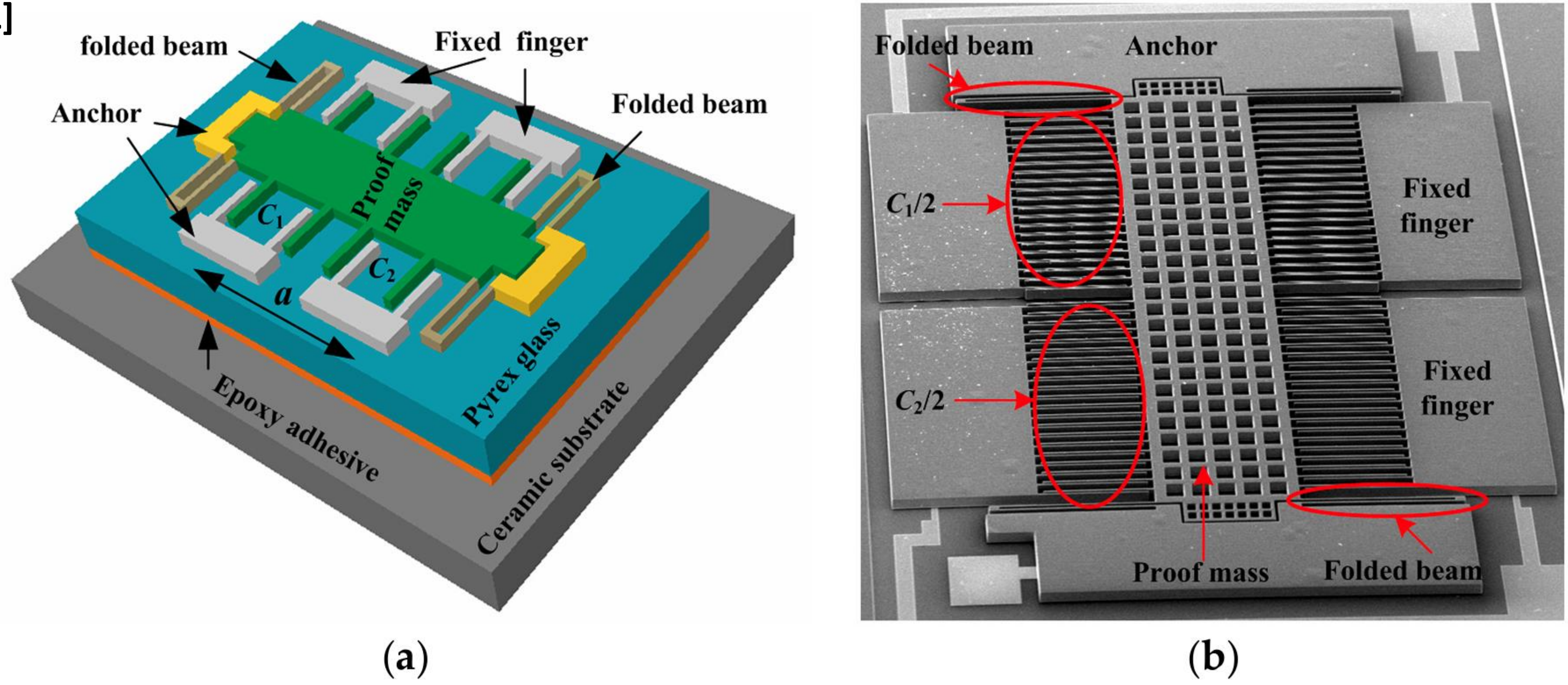
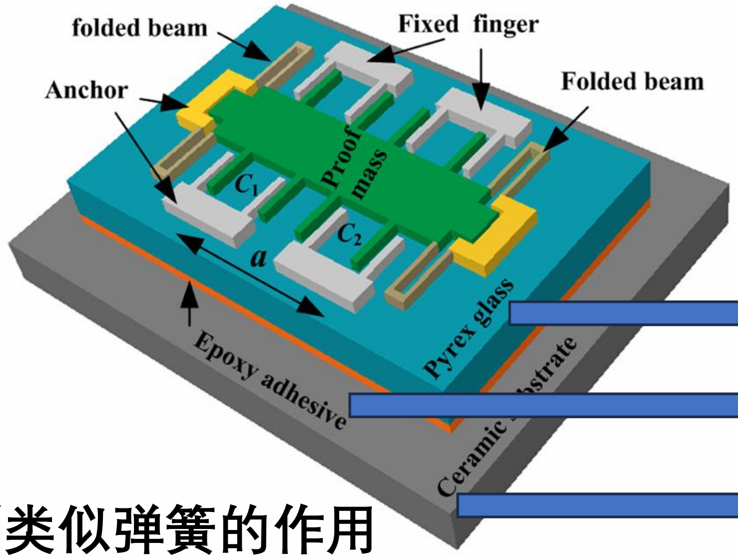


Figure 1. Structure of capacitive accelerometer. (**a**) Diagram of accelerometer; (**b**) SEM structure.

Capacitive accelerometer 核心resonator结构



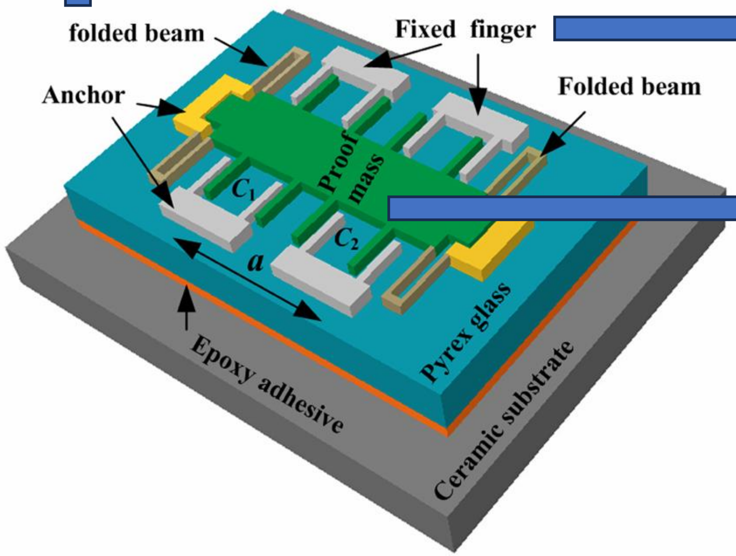
Pyrex glass（硼硅玻璃）支撑结构之一，常作为盖层/绝缘层使用，提供支撑和封装环境

Epoxy adhesive（环氧胶），用于把 MEMS 芯片粘接到封装基底（通常是陶瓷基板）上的胶粘材料。

Ceramic substrate（陶瓷基板）。整个传感芯片的基底

起到类似弹簧的作用

(a)



(a)

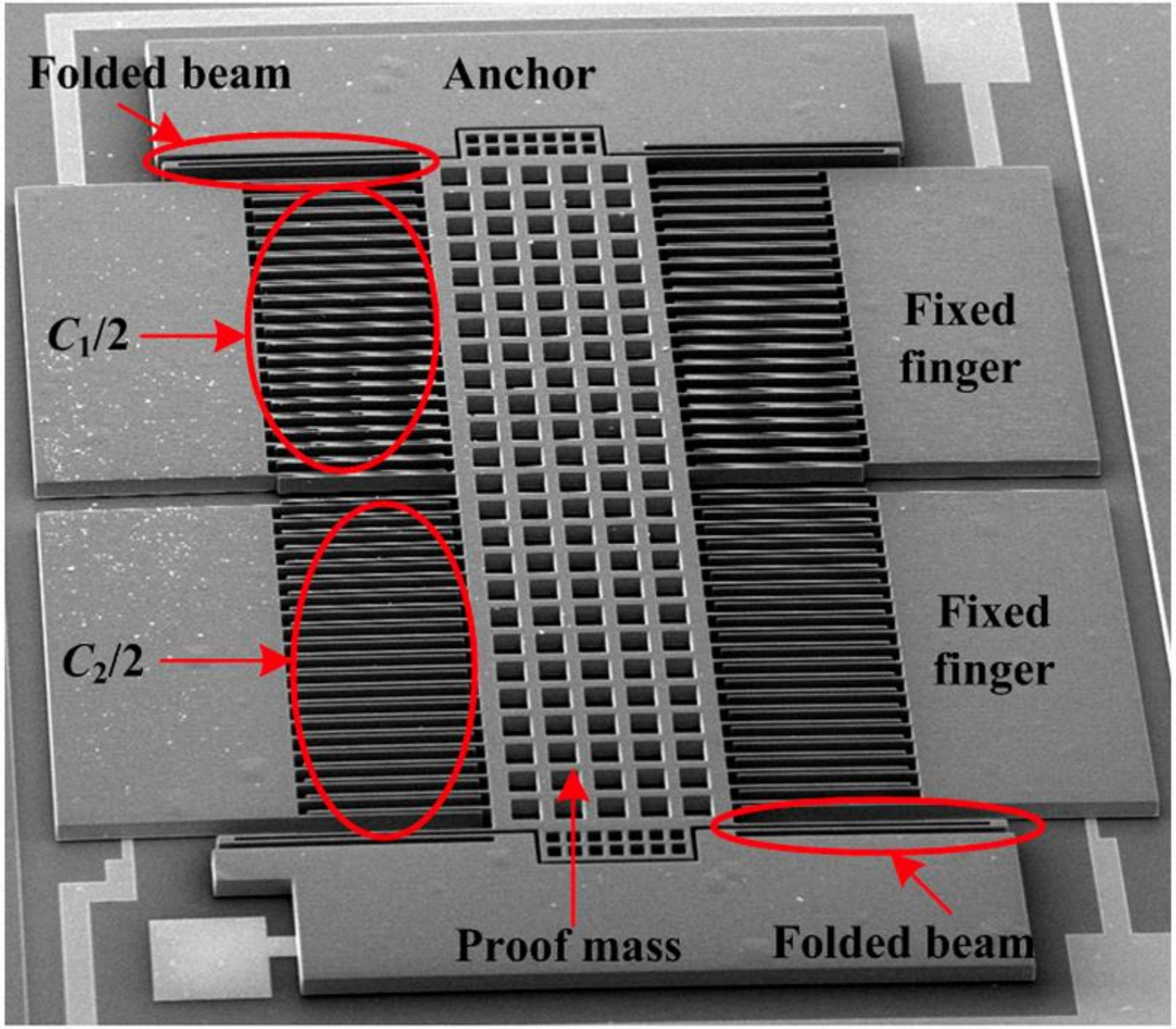
Fixed finger（固定电极）

白色结构，是电容式加速度计的固定部分，与质量块上的移动电极一起构成差动电容器（C_1 与 C_2），定梳齿

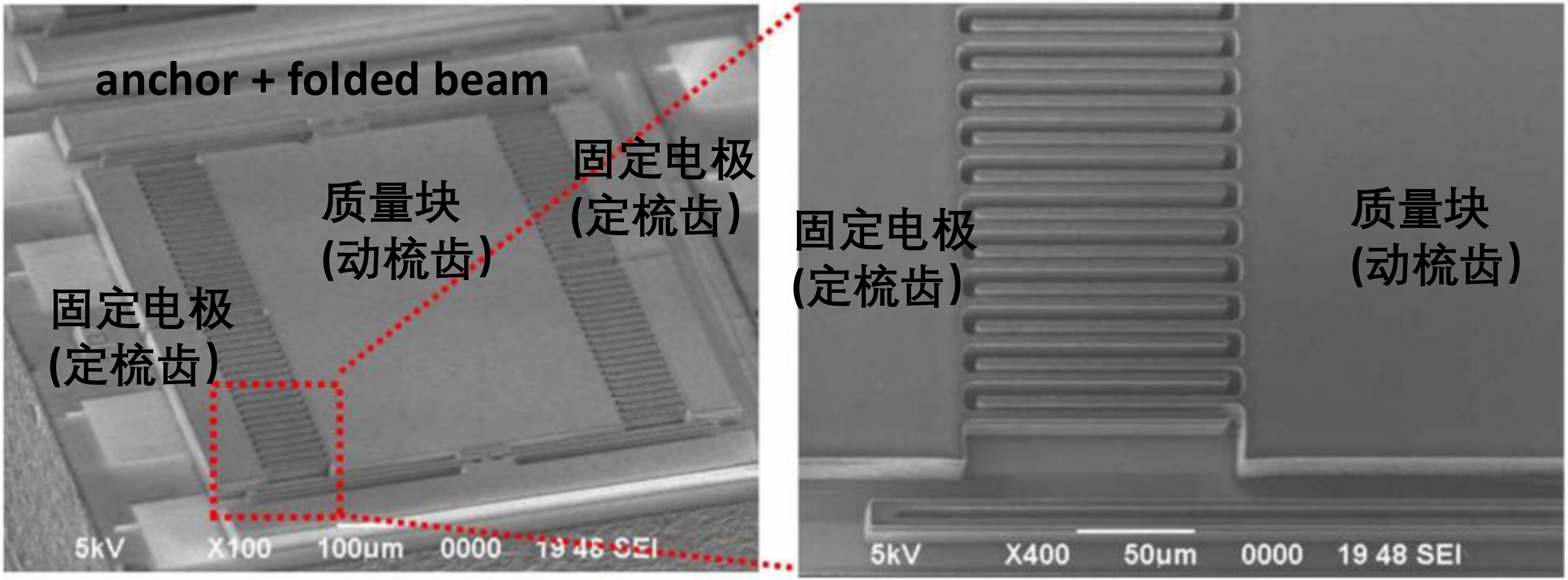
Proof mass（质量块） 加速度计的核心感应元件。在受到加速度作用时，它会由于惯性而发生微小位移，引起电容变化。

也就是动梳齿

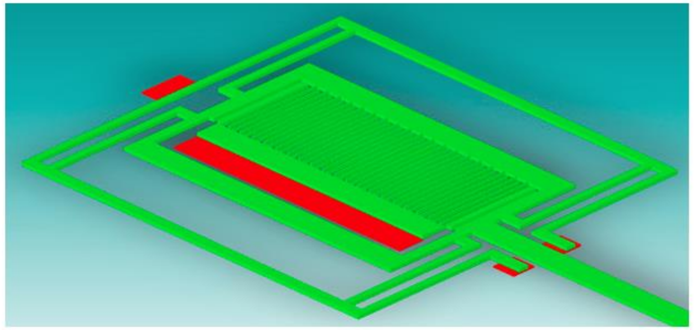
Capacitive accelerometer 核心resonator结构实际图

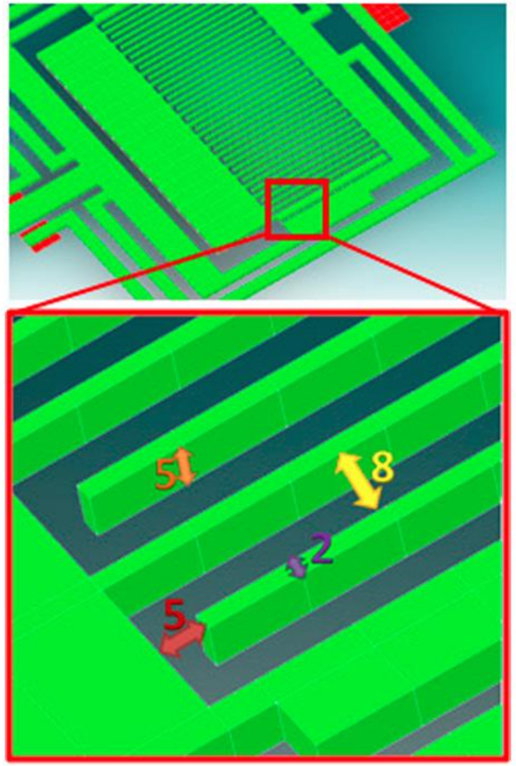


Capacitive accelerometer 核心resonator结构实际图



resonator结构实际尺寸





单位um

不同加速度下定梳齿移动距离

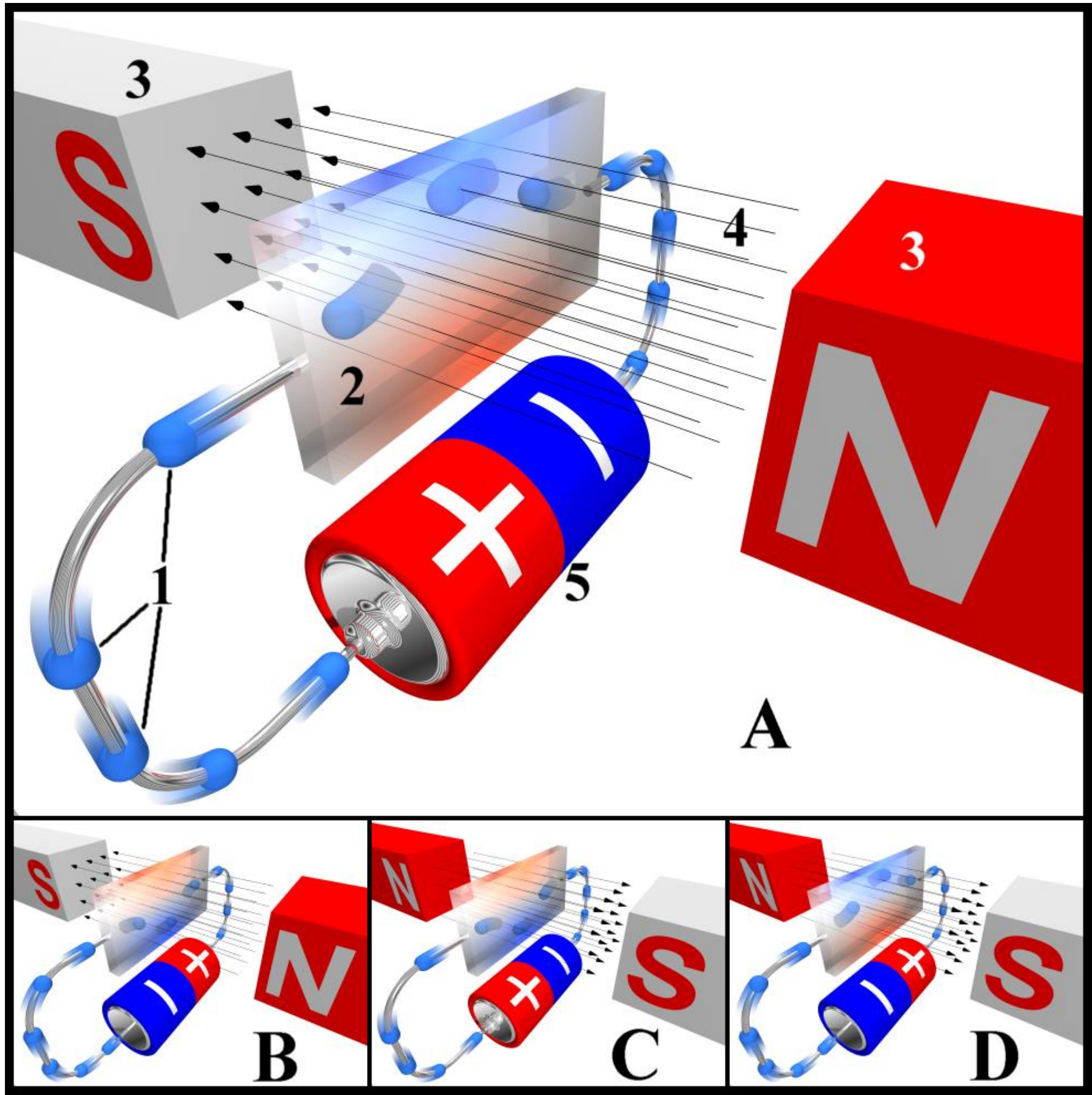
Table 2. The displacement of the seismic mass under acceleration.

Acceleration	Displacement
[m/s^2]	[nm]
0.5	0.054
1	0.120
1.5	0.160
2	0.220

梳齿移动距离~nm,远小于resonator电极板间隙

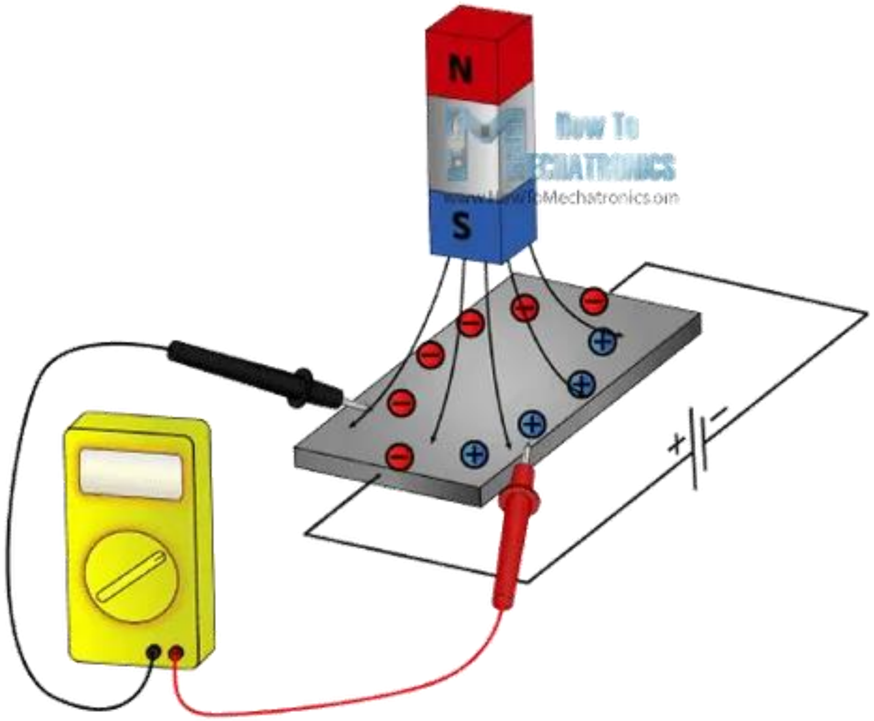
How Magnetometer Work

- Measures magnetic field strength (Tesla or Gauss)
- Foundation: Hall effect



How Magnetometer Work

- Measures magnetic field strength (Tesla or Gauss)
- Foundation: Hall effect + MEMS



Outline

- An Introduction of IMU
- **IMU Error Model**
- IMU Calibration

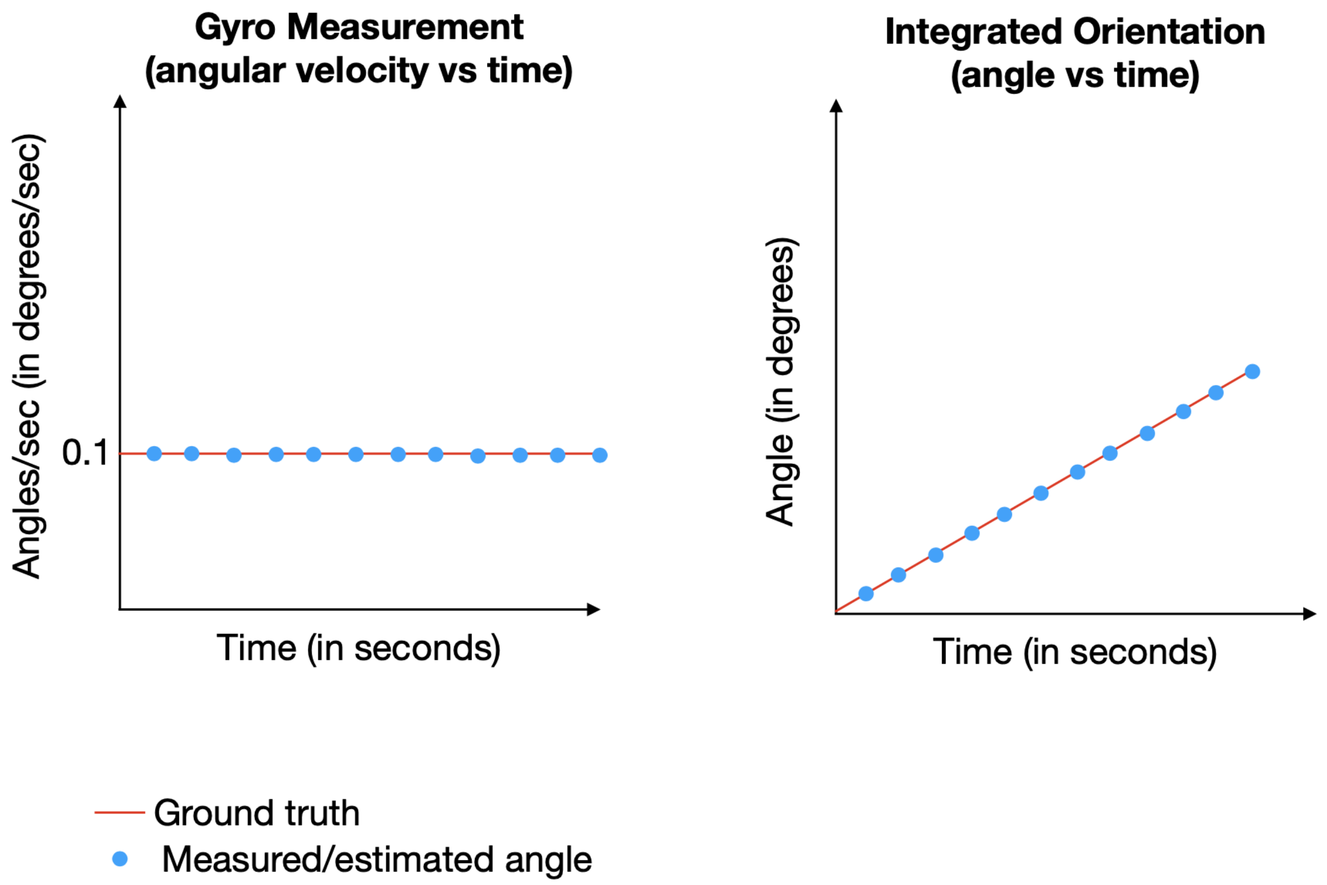
IMU Error Model

IMU Error Model

- Integration error for calculating position and angle
- Example
  - How to get from angular velocity to angle?
  - Integrate, knowing initial position

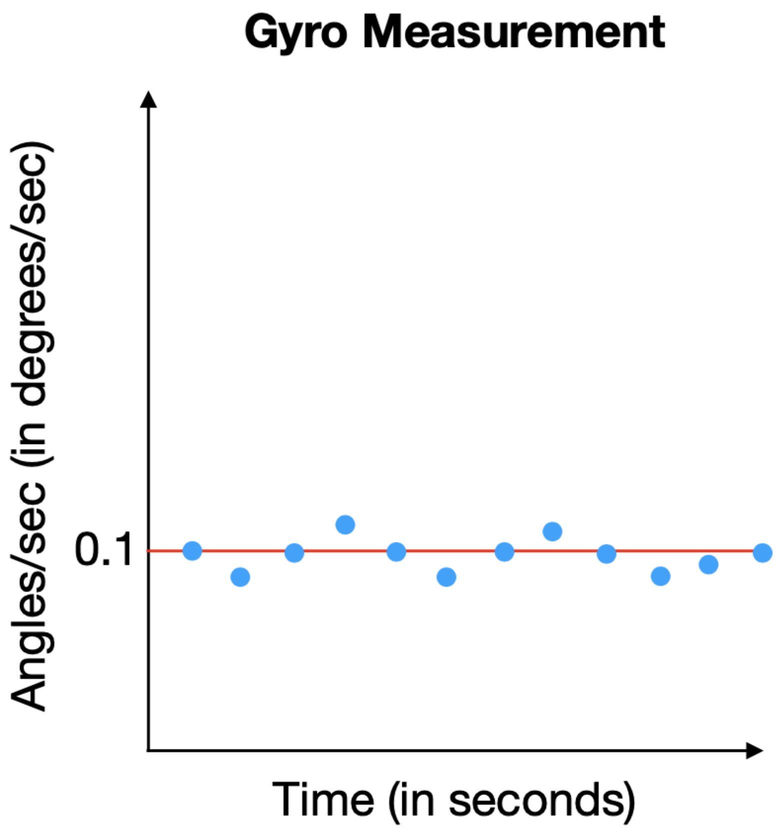
IMU Error Model: Angular Velocity → Angle

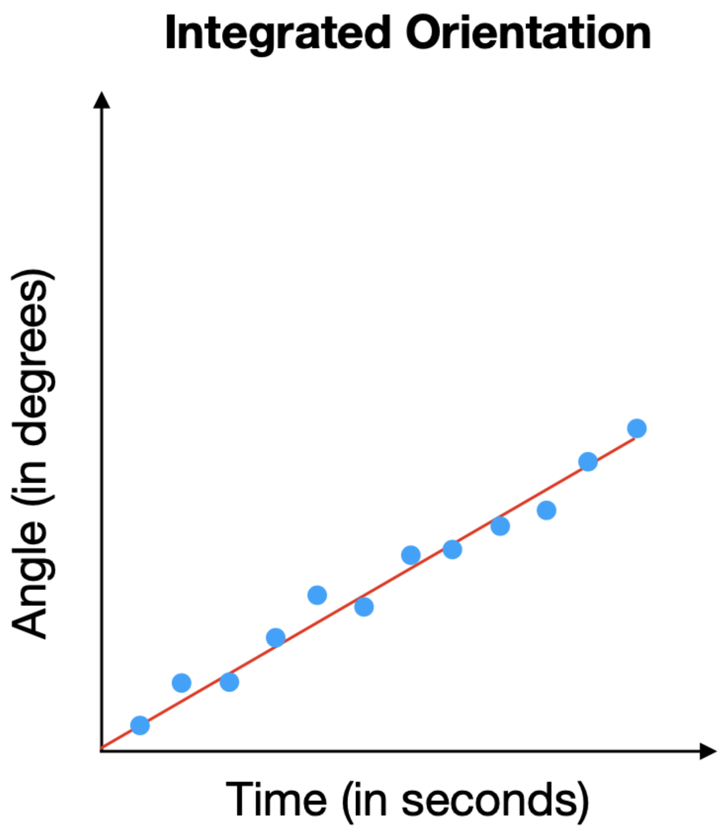
- no noise, no bias



IMU Error Model: Angular Velocity → Angle

- noise, no bias

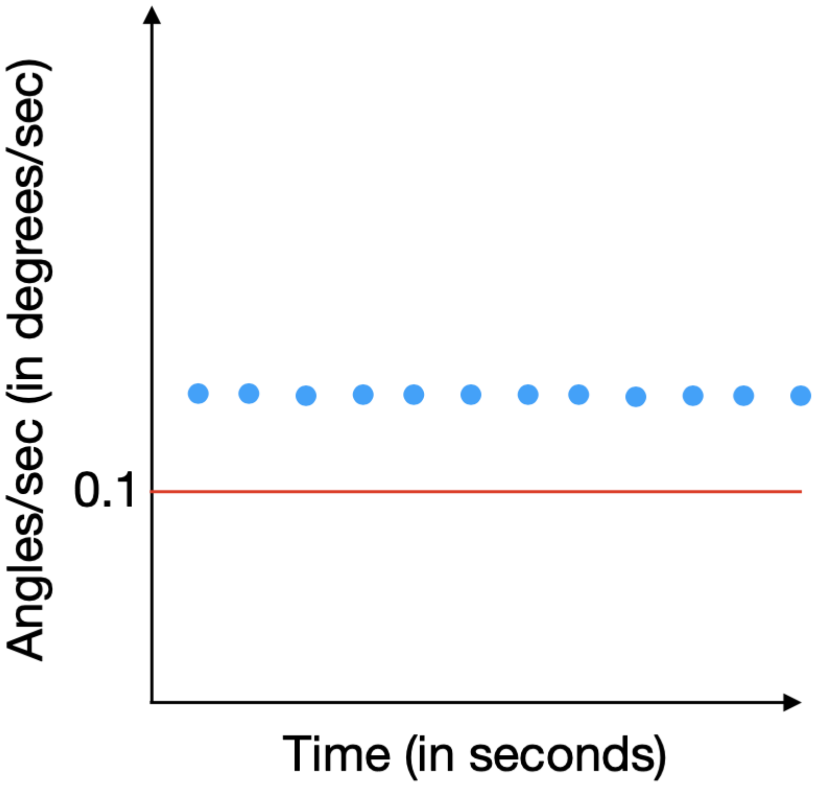




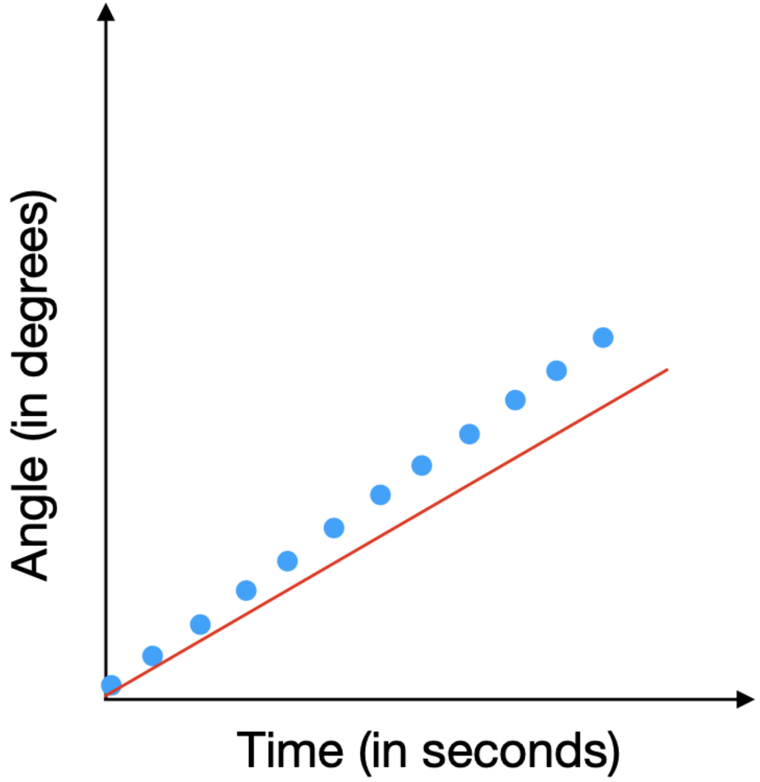
IMU Error Model: Angular Velocity → Angle

- no noise, bias

Gyro Measurement



Integrated Orientation



IMU Error Model

Error of IMU raw data[3]:

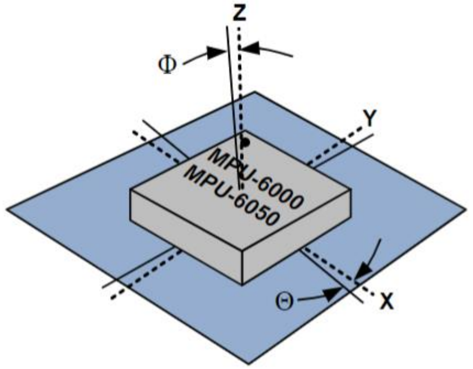
- Deterministic error 确定性误差
  - misalignment/nonorthogonality **between the axes**
  - bias (zero-g/zero-rate level offset)
  - scale factor
- 随机误差 stochastic error
  - flicker noise
  - random sensor noise

[3]D. Unsal and K. Demirbas, "Estimation of deterministic and stochastic IMU error parameters," *Proceedings of the 2012 IEEE/ION Position, Location and Navigation Symposium*, 2012, pp. 862-868, doi: 10.1109/PLANS.2012.6236828.

IMU Error Model

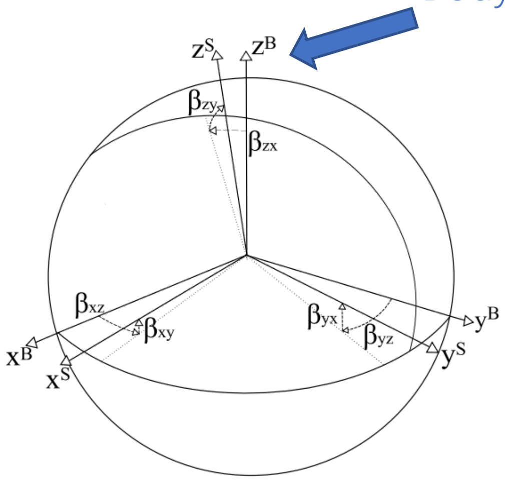
misalignment / nonorthogonality between the axes:

加速度、角速度坐标系不重合



Root cause: mechanical components cannot be produced perfectly/PCB package

Body frame



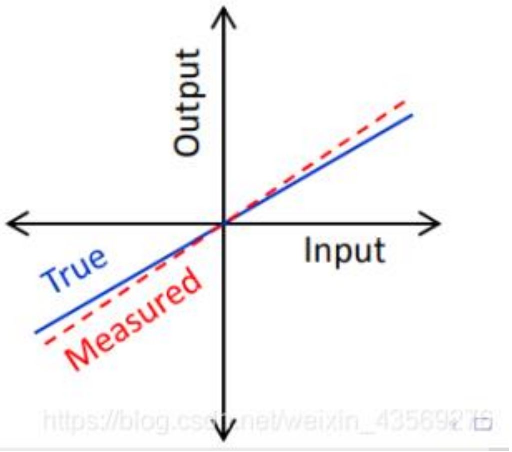
Calibration matrices

$$\mathbf{a}^O = \mathbf{T}^a \mathbf{a}^S, \qquad \mathbf{T}^a = \begin{bmatrix} 1 & -\alpha_{yz} & \alpha_{zy} \\ 0 & 1 & -\alpha_{zx} \\ 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{\omega}^O = \mathbf{T}^g \boldsymbol{\omega}^S, \qquad \mathbf{T}^g = \begin{bmatrix} 1 & -\gamma_{yz} & \gamma_{zy} \\ \gamma_{xz} & 1 & -\gamma_{zx} \\ -\gamma_{xy} & \gamma_{yx} & 1 \end{bmatrix}$$

IMU Error Model

scale factor (存在一个比例因子)



Root Cause： introducd from **A/D conversion**

Calibration matrix: scaling matrices

$$\mathbf{K}^a = \begin{bmatrix} s_x^a & 0 & 0 \\ 0 & s_y^a & 0 \\ 0 & 0 & s_z^a \end{bmatrix}, \qquad \mathbf{K}^g = \begin{bmatrix} s_x^g & 0 & 0 \\ 0 & s_y^g & 0 \\ 0 & 0 & s_z^g \end{bmatrix}$$

0*g* on the X- and Y-axes and +1*g* on the Z-axis. The accelerometers' scale factor is calibrated at the factory and is nominally independent of supply voltage. Each sensor has a dedicated sigma-delta ADC for providing digital outputs. The full scale range of the digital output can be adjusted to ±2*g*, ±4*g*, ±8*g*, or ±16*g*.

MPU6050 datasheet

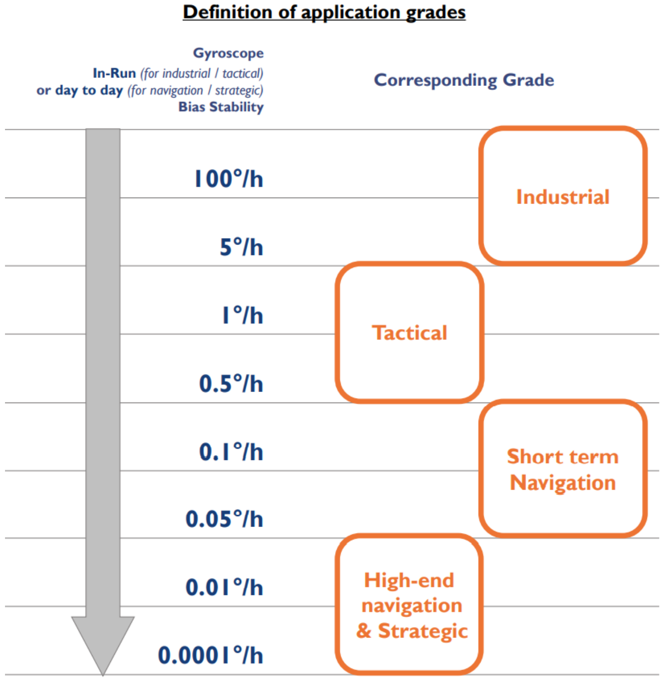
IMU Error Mode

bias (zero-g/zero-rate level offset) + flicker noise(**bias Instability):**

零偏

- 闪烁噪声 (零偏不稳定性）：零偏会随时间温度缓慢变化
- 即：静止时，衡量陀螺仪输出量围绕其均值（零偏）的离散程度

Root Cause： quite complex, e.g., sensitive to environment/temperature



Calibration: two bias vectors

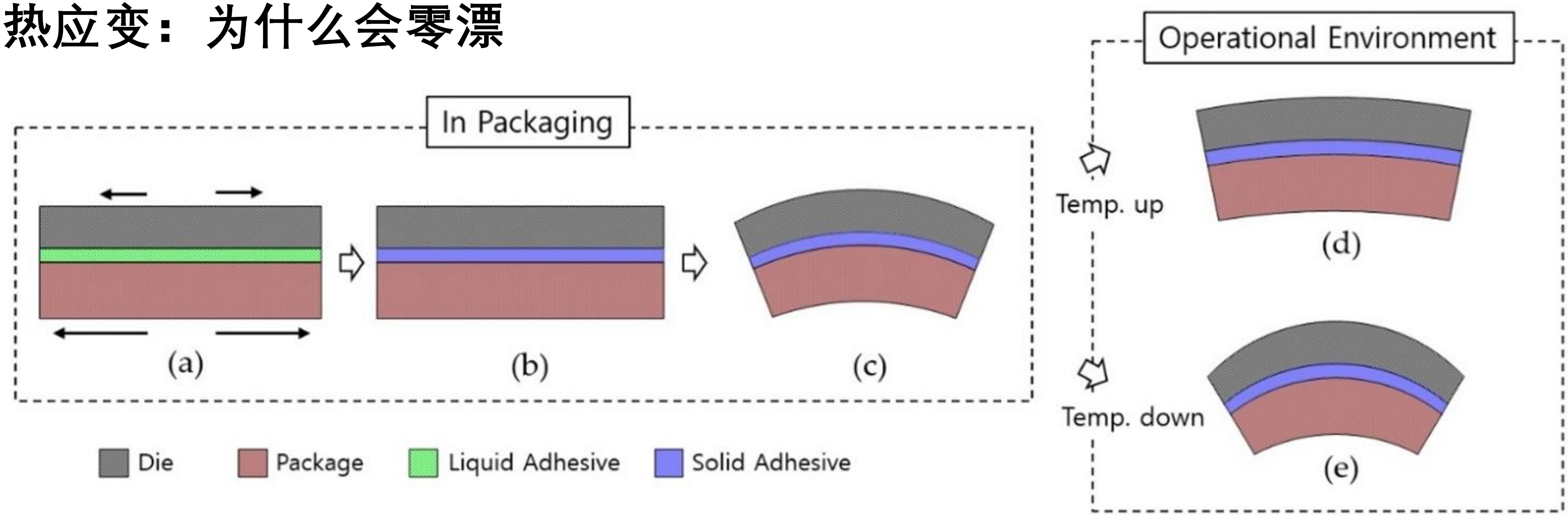
$$\mathbf{b}^a = \begin{bmatrix} b_x^a \\ b_y^a \\ b_z^a \end{bmatrix}, \qquad \mathbf{b}^g = \begin{bmatrix} b_x^g \\ b_y^g \\ b_z^g \end{bmatrix}$$

Note:

- The bias is different every time you turn an IMU on due to flicker noise
- The bias is different even if the IMU is operating after a long time

[4]High-end Inertial Sensors for Defense, Aerospace, and Industrial Applications, YoleDéveloppement

热应变：为什么会零漂



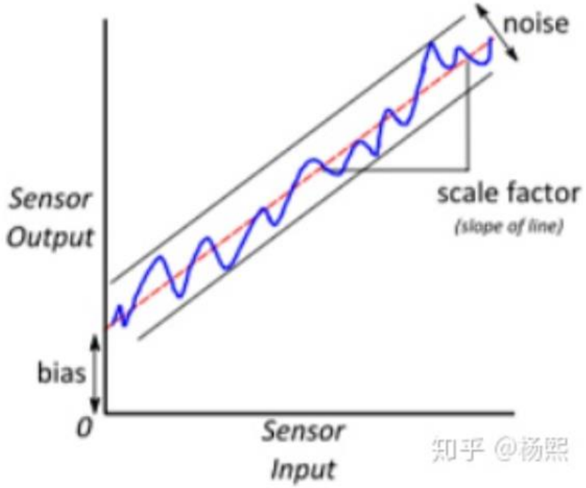
芯片粘接（die attach）：通常也是产生热应力的主要来源

通常，MEMS 传感器的**封装材料(Package)**的热膨胀系数要**大于芯片材料(Die)**
在封装过程中，当温度升高至**胶水固化温度**之前，封装体**(Package)**比芯片**(Die)**膨胀得更多（图 1a）
此时，封装体和芯片已膨胀到不同程度，随后在固化温度下用胶水固定在一起（图 1b）
在随后的冷却过程中，由于封装体与芯片的**收缩速率不同**，会产生热应力，使得整个结构发生变形，向下凹陷（图 1c）

在工作环境中，这种称为“**芯片翘曲（die warpage）或封装应力（packaging stress）**”的变形，会随温度变化而波动：温度升高时减小，温度降低时增强（图 1d、1e）

IMU Error Model

random sensor noise



Root Cause: sensitive to environment/temperature/pressure.

How to express in calibration model:

$\boldsymbol{\nu}^{g}$

IMU Error Model: In Summary

Complete sensor error model:

$$\mathbf{a}^O = \mathbf{T}^a\mathbf{K}^a(\mathbf{a}^S + \mathbf{b}^a + \boldsymbol{\nu}^a)$$

$$\boldsymbol{\omega}^O = \mathbf{T}^g\mathbf{K}^g(\boldsymbol{\omega}^S + \mathbf{b}^g + \boldsymbol{\nu}^g)$$

Calibrated data

Converting matrix

scaling matrix

raw data

bias vector

random sensor noise

For low-precision use:
Only need to evaluate the bias of IMU

For relative high-precision use:
Each error parameter should be carefully evaluated

Outline

- An Introduction of IMU
- IMU Error Model
- IMU Calibration

IMU Calibration

Use the calibrated accelerometer to calibrate gyroscope:

Correct the accelerometer reading

Calculate the attitude in the static interval by g

Integrate the gyro reading to estimate the attitude

$$\mathbf{u}_{g,k} = \Psi\left[\omega_i^S, \mathbf{u}_{a,k-1}\right]$$

(attitude estimate by gyro)

(attitude given by acce in last interval)

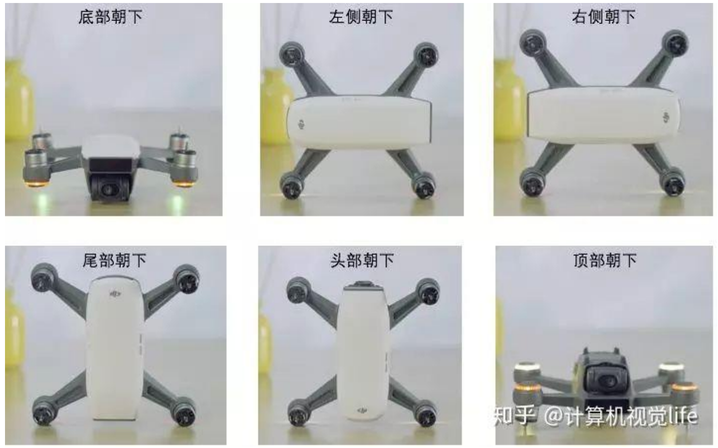
Cost function:

$$\mathbf{L}(\boldsymbol{\theta}^{gyro}) = \sum_{k=2}^{M} ||\mathbf{u}_{a,k} - \mathbf{u}_{g,k}||^2$$

Estimate the parameter

Other calibration method:

Six - sided calibration method

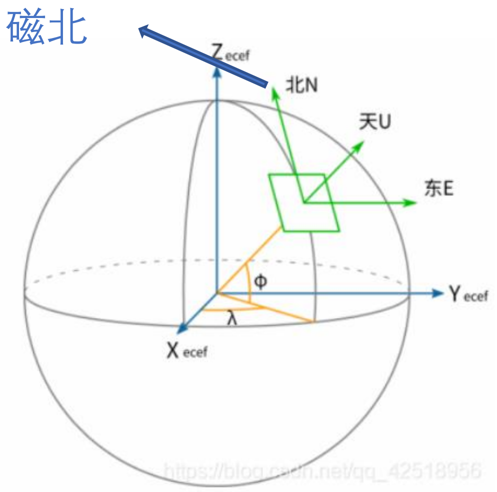


High precision turntable

IMU for Altitude Estimation

Something need to know before estimating attitude:

1、Earth coordinate(ENU)



The attitude refers to the change between ENU and IMU's own coordinate(body frame)

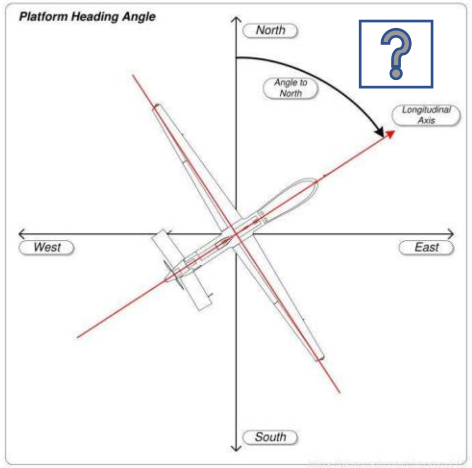
2、Euler angle →Expression quaternion(四元数)→ calculation

Euler angle:

Yaw/Pitch/Roll(Z-Y-X)

IMU for Altitude Estimation

accelerometer :



Use gravity to calibrate:

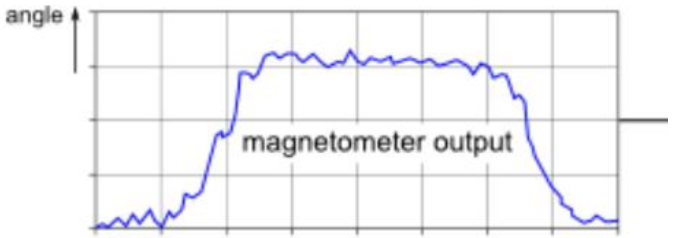
1、IMU keep moving:

acceleration= a+ g

2、difficult to calculate

yaw angle

magnetometer:



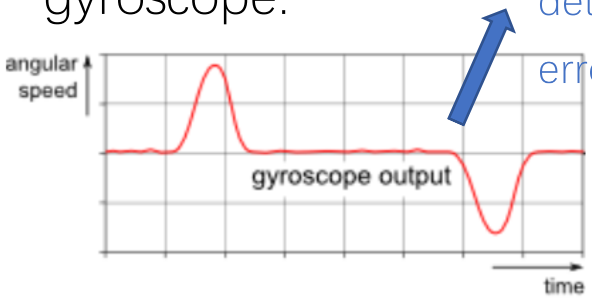
Use earth magnetic field to calibrate:

1、suffer from high frequency noise, calculated pose will oscillate

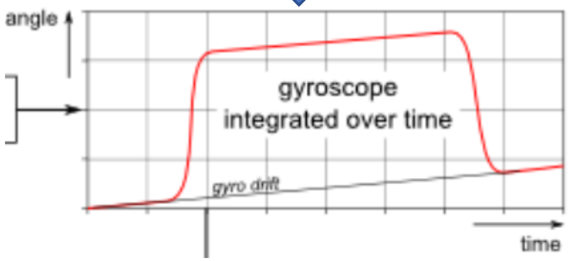
2、sensitive to magnetic interference

gyroscope:

Suffer from deterministic error/noise



Σ



Use integration of angular rate:

drift problem

Sheng Shen, Mahanth Gowda, and Romit Roy Choudhury. 2018. Closing the Gaps in Inertial Motion Tracking. In Proceedings of the 24th Annual International Conference on Mobile Computing and Networking (MobiCom '18). https://doi.org/10.1145/3241539.3241582

Crash detection

- https://www.bilibili.com/video/BV1Be4y1h7pe/?spm_id_from=333.337.search-card.all.click
  - (1:32:18 – 1:32:48)

References

- Sheng Shen, Mahanth Gowda, and Romit Roy Choudhury. 2018. Closing the Gaps in Inertial Motion Tracking. In Proceedings of the 24th Annual International Conference on Mobile Computing and Networking (MobiCom '18). Association for Computing Machinery, New York, NY, USA, 429–444. https://doi.org/10.1145/3241539.3241582