life.augmented

ST MEMS inclinometers for accurate angle measurements & structural health monitoring

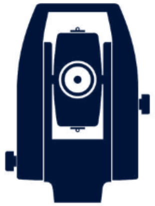
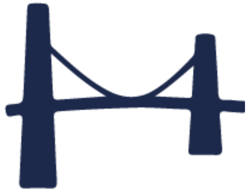
STMicroelectronics

Werner NEUMANN, MEMS Marketing Senior Manager

Agenda

life.augmented

Inclinometers in industrial applications

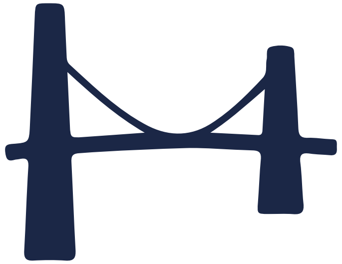
Pointing, levelling and stabilization	Robotics and I-IoT	Inclinometers for industrial vehicles	Equipment Installation and monitoring	Leveling Instruments	Structural Health Monitoring
					
Antenna pointing, platform leveling and stabilization	Robotics and Industrial automation	High accuracy inclinometers for industrial vehicles, forklift, construction machines	Installation and monitoring of equipment, tracker for solar panels	Precise leveling instruments	Building and infrastructure condition monitoring (inclination and low frequency vibration)

Inclinometers accurately measure a tilt angle under static or quasi-static conditions.
To measure angles of objects in highly dynamic conditions, see also
Dynamic Inclinometer using 6-axis IMU in st.com

life.augmented

Inclinometers for Structural Health Monitoring

Measuring inclination and low-frequency, low-level vibrations with high resolution and repeatability



Buildings

Towers

Monuments, geophysics civil structures

Dams, tunnels

Roads & bridges

ST Sensors Longevity Program
A complete portfolio

LONGEVITY 10 YEARS COMMITMENT

life.augmented

Accelerometers	Inclinometers	Vibration sensors

LONGEVITY 10 YEARS COMMITMENT

- High performance
- High accuracy
- High reliability

6-axis IMU + Machine Learning	Temperature sensors	High-bandwidth microphones

Tilt sensing theory

life.augmented

Tilt measurement with an accelerometer

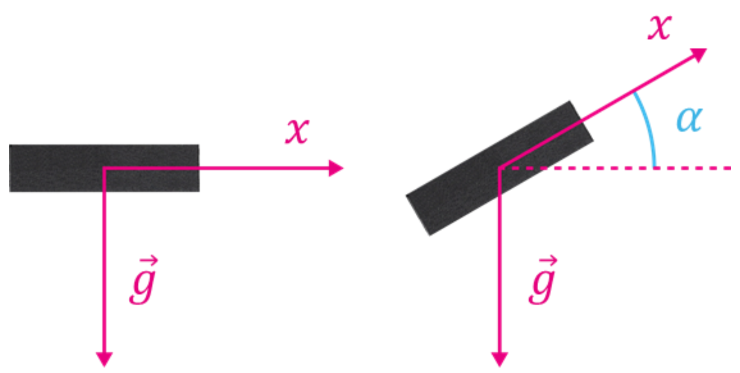
- Tilt measurement with an accelerometer is based on projection of the Gravity vector on its sensing axes
- An accelerometer does not measure only the gravitational acceleration, but any acceleration caused for example by:
  - Constant acceleration of the device
  - Centripetal acceleration due to a rotation of the device
  - Vibrations, for example due to a running machine or engine nearby

- Such accelerations cannot be easily differentiated from gravitational acceleration and can introduce measurement errors
- Therefore, accurate results require static or quasi-static conditions

Inclinometers are high-accuracy accelerometers for angle measurements

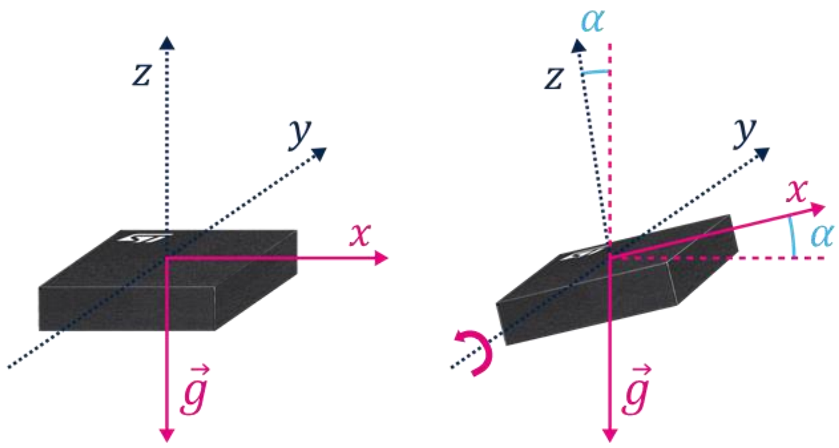
Single-axis tilt measurement

- Single-axis tilt measurement is suitable only for applications where a small range of tilt angles is required, or where lower accuracy is accepted
- The output value of an accelerometer is equal to the sine of the tilt angle, α, between the horizontal plane and sensing axis



$$A_x\,[g] = 1g \cdot sin(\alpha)$$

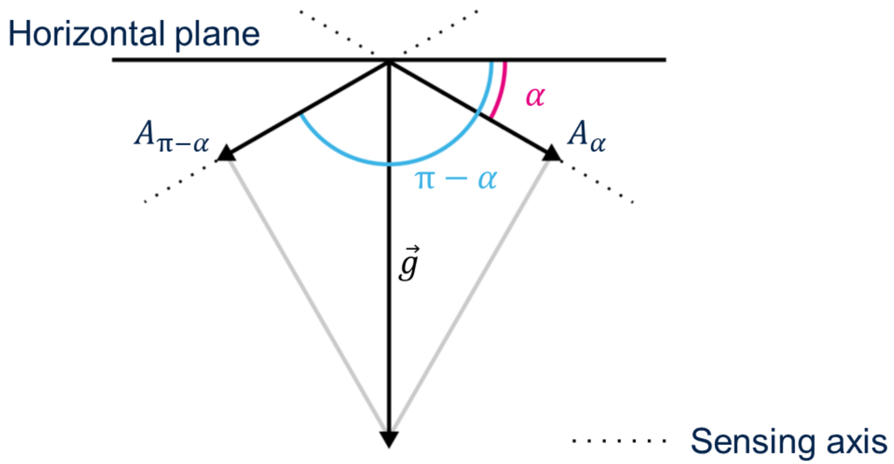
$$\alpha[rad] = asin\left(\frac{A_x}{1g}\right)$$



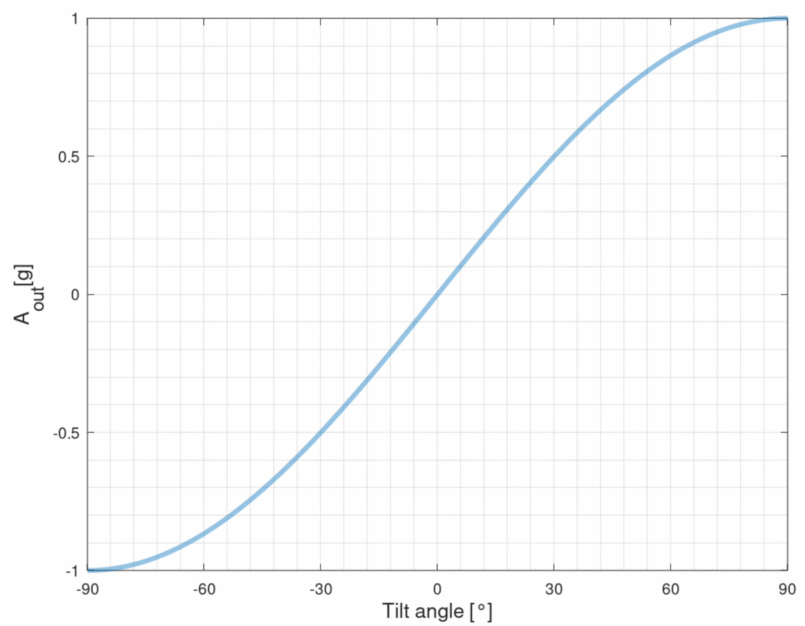
Note: $\alpha[°] = \alpha\,[rad] \cdot \left(\frac{180}{\pi}\right)$

Single-axis tilt measurement

- It is not possible to cover the full 360˚ range when measuring the α angle with a single-axis solution, as the output of an accelerometer is the same for angle $\alpha[rad]$ and $\pi - \alpha[rad]$
- The sensitivity (change of the output based on change of the input) of the tilt calculation is the highest around 0° and decreases with angle of inclination

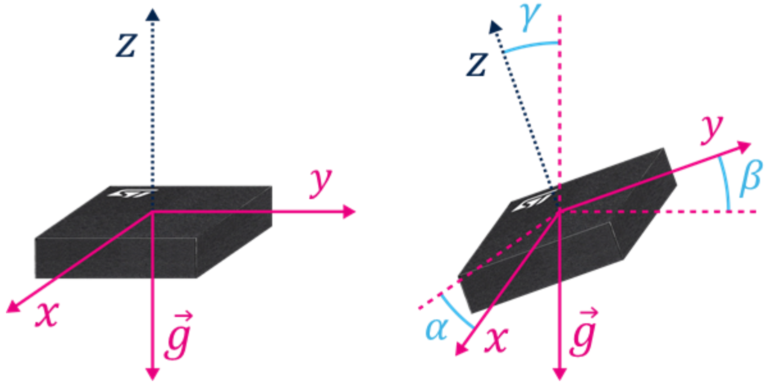


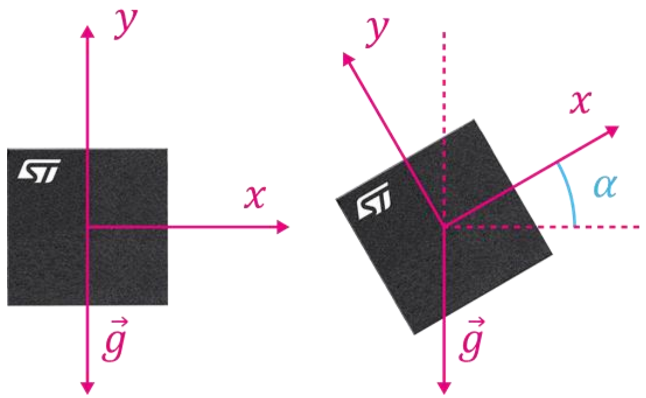
Measurement range: $\alpha = [-90°, +90°]$



Dual-axis tilt measurement

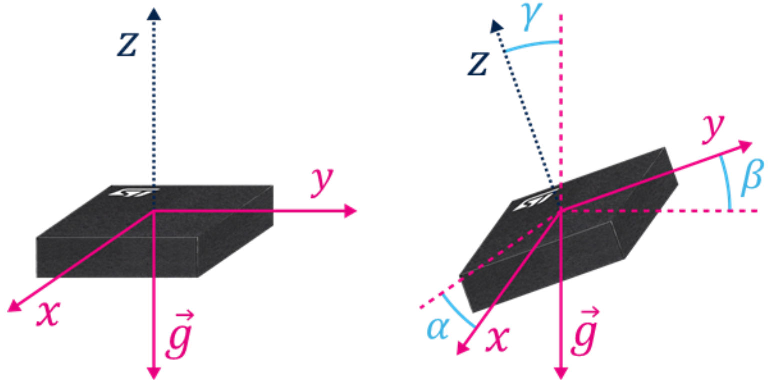
- There are two commonly used reference orientations of the sensor for dual-axis tilt measurement
- Each orientation is suitable for different kinds of applications
- It is possible to split such applications into two categories:
  - Measure tilt angles around both axes (pitch and roll)
  - Measure a tilt angle in a complete 360° arc





Dual-axis tilt measurement Horizontal placement

- The reference position of the sensor is when its X and Y axes are in horizontal plane:



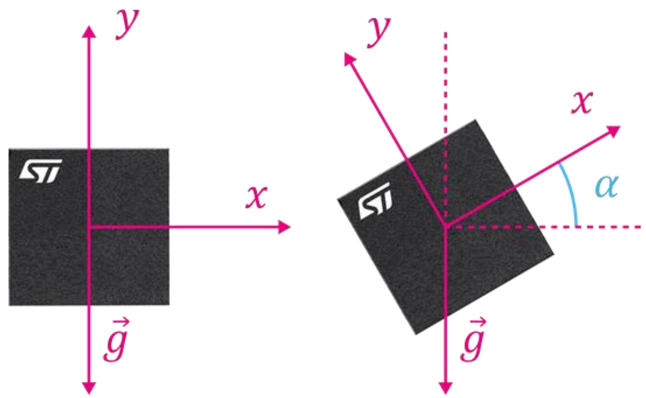
- Such orientation allows measurement of tilt angles around both axes (α and β), but it has the same drawbacks as single-axis tilt measurement:
  - It is not possible to cover the full 360˚ range around each axis
  - The sensitivity of the tilt calculation is not constant over the tilt angle range

Dual-axis tilt measurement
Vertical placement

- The reference position of the sensor is when its X axis lies in the horizontal plane and Y axis points up (towards sky)
- This orientation of the sensor is used in applications where higher accuracy and/or the ability to measure tilt angle in a complete 360° range is required:

$$A_x\,[g] = 1g \cdot sin(\alpha)$$

$$A_y\,[g] = 1g \cdot cos(\alpha)$$



$$\frac{A_x}{A_y} = \frac{1g \cdot sin(\alpha)}{1g \cdot cos(\alpha)} = \tan(\alpha)$$

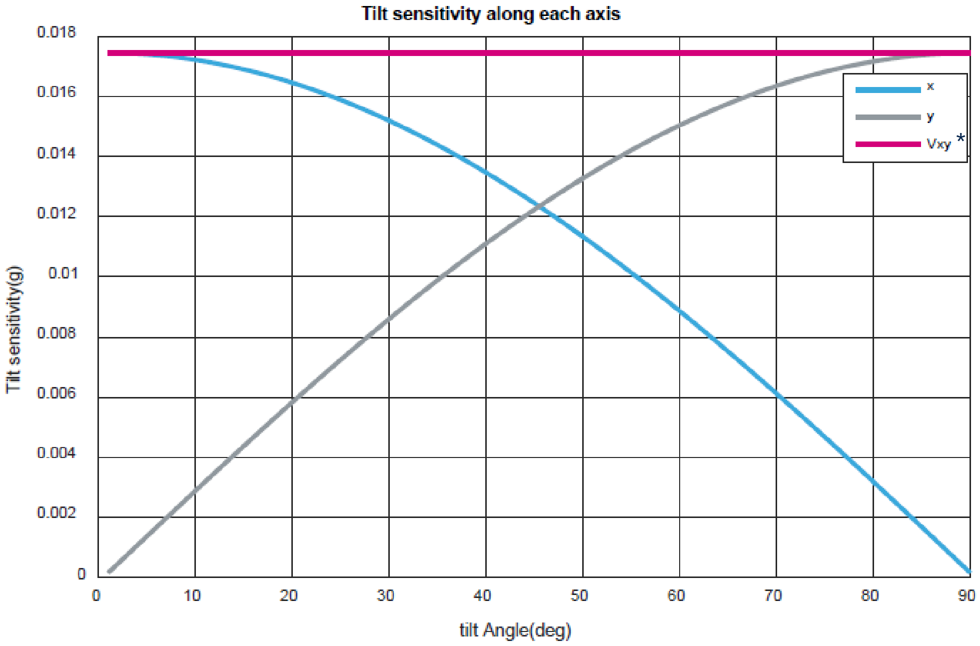
$$\alpha[rad] = \text{atan}\left(\frac{A_x}{A_y}\right)$$

Warning: the atan(A_x / A_y) function requires quadrant corrections and exception handling. It is possible to use the atan2(A_x, A_y) function instead (the correction is implemented).

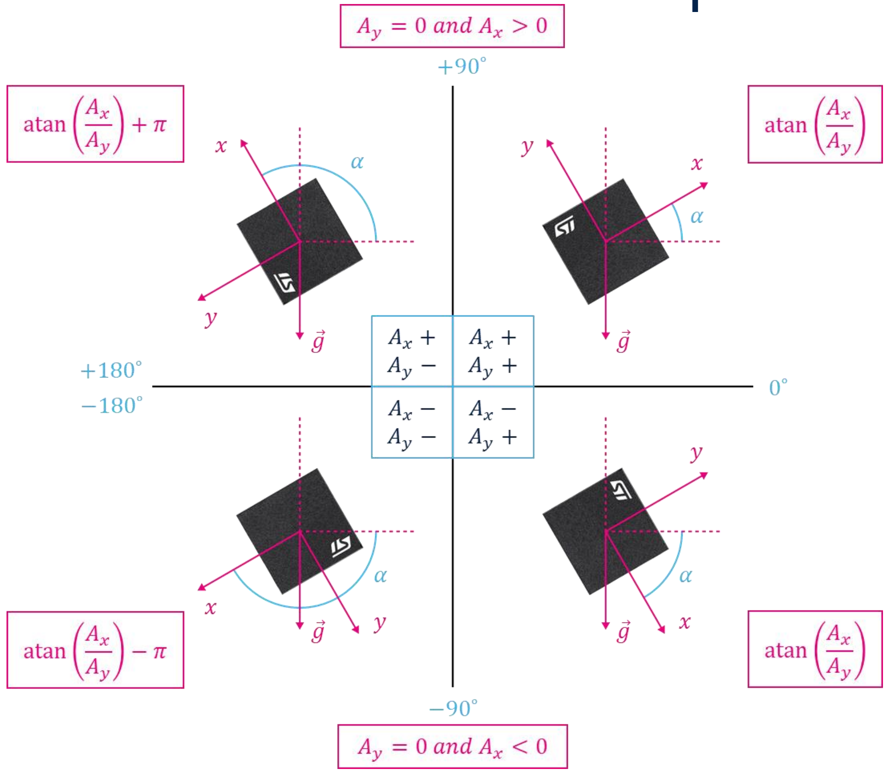
life.augmented

Dual-axis tilt measurement
Vertical placement

- When the tangent function is used, the inclination sensitivity over the full inclination angle range is constant
- It is also possible to measure over the entire range of 360° inclination because the orientation can be distinguished from the sign of the accelerometer outputs



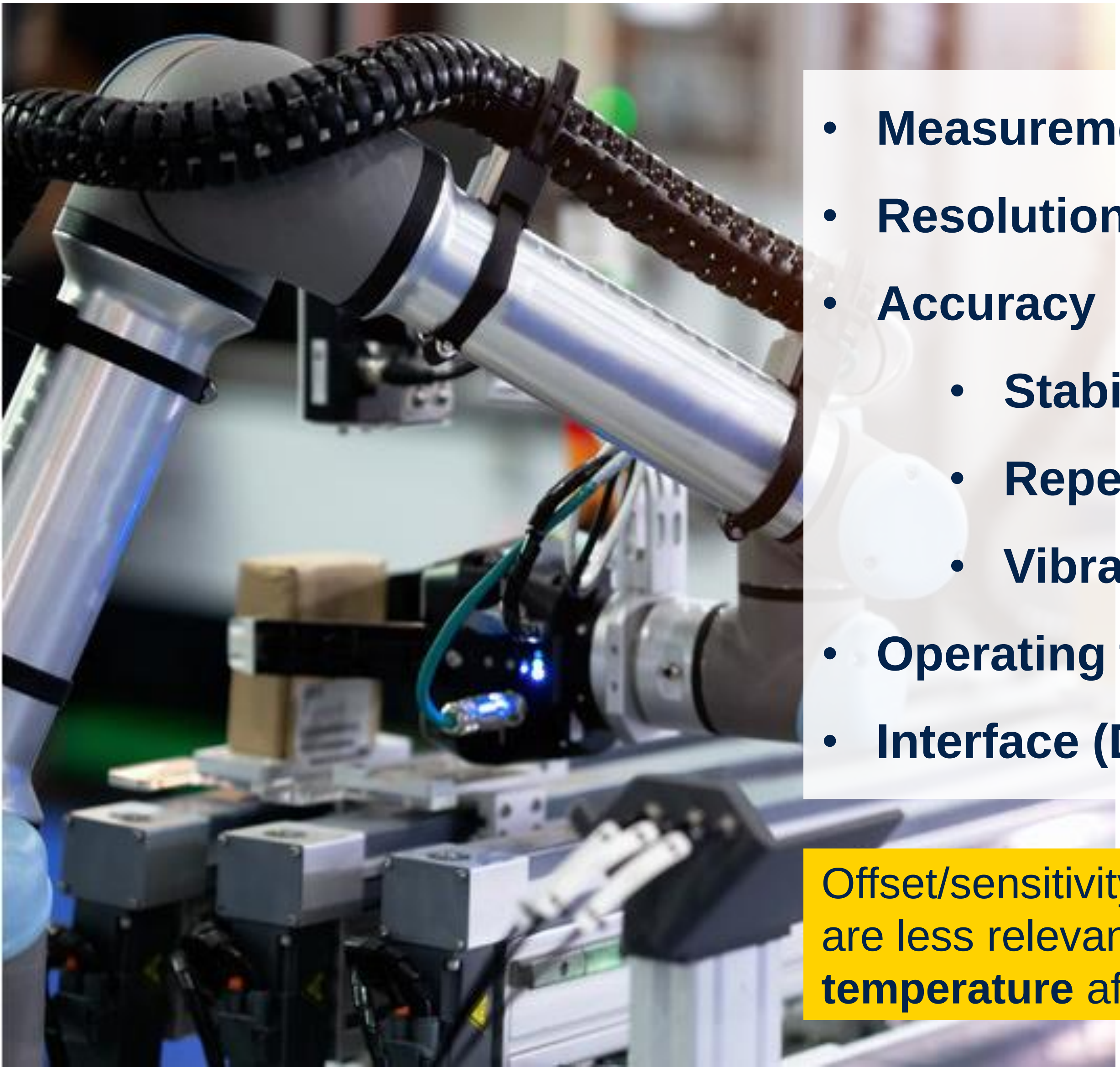
* Vxy – atan function used



IIS2ICLX 2-axis inclinometer: details and accuracy

life.augmented

KPIs for inclinometers



- **Measurement range (full scale)**
- **Resolution (noise)**
- **Accuracy**
  - **Stability over temperature**
  - **Repeatability**
  - **Vibration rectification (VRE)**
- **Operating temperature range**
- **Interface (Digital or Analog)**

Offset/sensitivity, post solder drift, cross-axes and non-linearity errors are less relevant because they can be calibrated at **ambient temperature** after soldering the component

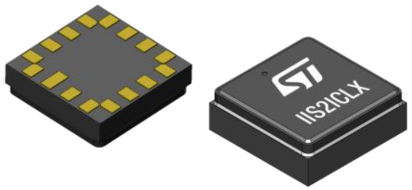
IIS2ICLX
High-accuracy 2-axis digital inclinometer

Ultra-high-accuracy, high-resolution, low-power,
2-axis digital inclinometer with embedded Machine Learning Core

Key Features

- 2-axis, digital plug & play inclinometer
- Top performance: resolution, accuracy, stability over temperature and time
- **Accuracy better than 0.5° over full temperature range and over time**
- **Ultra-low noise (15 µg/√Hz)**
- Low power
- **Programmable Machine Learning Core & Finite State Machines** to integrate AI algorithms and reduce power consumption at system level
- **Extended operating temperature range: from -40 to +105 °C**

Parameter	Value
N. of axes	**2-axis**
Full Scale [g]	± 0.5/1.0/2.0/3.0
Output i/f	Digital I2C/SPI
Bandwidth (-3dB) [Hz]	Programmable, up to 260
ODR [Hz]	12.5 to 833
Noise Density [µg/√Hz]	**15**
Offset change vs Temp [mg/°C]	**<0.075**
Current consumption [mA]	0.42
Features	**MLC (Machine Learning Core)** FSM (Finite State Machine) Sensor HUB FIFO (3kbyte), Interrupts Embedded Temp. Sensor
Operating Temp [°C]	**-40 ; +105**
Operating Voltage [V]	1.71 ÷ 3.6



Ceramic Cavity LGA 5x5x1.7 16L

IIS2ICLX: tilt angle error estimations

IIS2ICLX	Value	Tilt angle error
Sensitivity error	2 %	0.6 deg (using 2 axis)
Sensitivity change over life	0.7 %	0.2 deg
Sensitivity change over temperature	0.01 %/ °C	0.2 deg at max. error at 105 °C
Zero-g level offset	8 mg	0.75 deg at 30 degrees
Zero-g level offset over life	2.5	0.25 deg at 30 degrees
Zero-g level offset over temperature	0.02 mg/°C	0.16 deg at 30 degrees at 105 °C
Noise density	15 µg/√(50)	0.005 deg at 95 ug RMS
VRE at 50Hz, 2.5g RMS	1 mg	0.1 deg
Operating temperature range	-40 to 105 °C	-

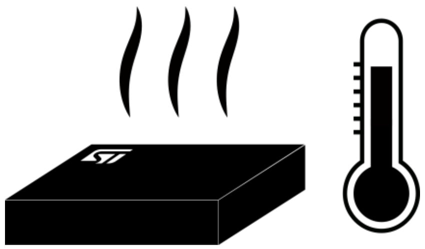
Sensitivity and Zero-g level recommended to be calibrated in production

Application Note AN5551
– Precise and accurate tilt sensing in industrial applications

life.augmented

Why calibrate the sensor?

- Each ST accelerometer is factory calibrated to match the parameters specified in the datasheet
- Accuracy of the inclination angle measurement can be affected by assembly processes on customer production lines, including:
  - thermal stresses during soldering
  - rotation of the accelerometer package relative to the circuit board
  - misalignment of the circuit board to the final product
- Applications that require higher accuracy such as antenna pointing, platform leveling, and leveling instruments require calibration after assembly in the final product

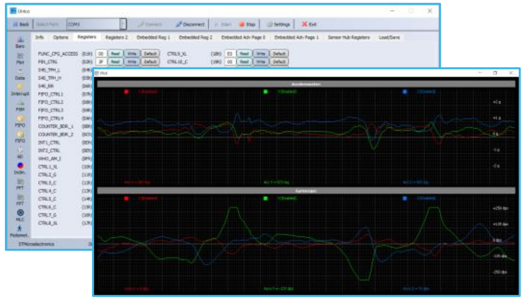


life.augmented

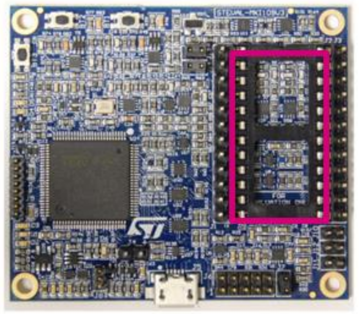
IIS2ICLX 2-axis Inclinometer: HW & SW Tools for evaluation

life.augmented

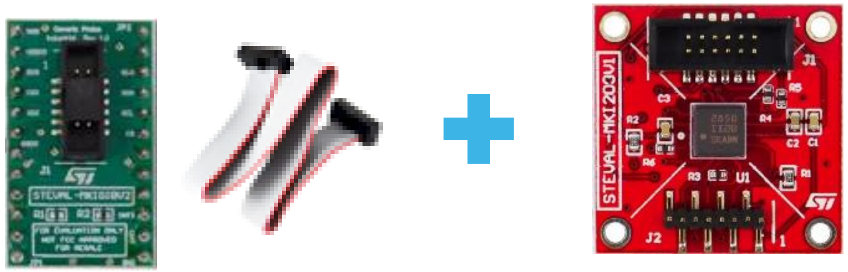
Development tools for the IIS2ICLX



PC Application
Unico-GUI

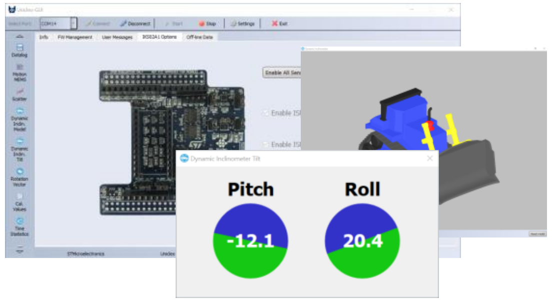


Professional MEMS motherboard
STEVAL-MKI109V3

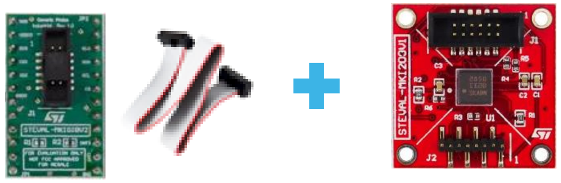


DIL24 adapter board
STEVAL-MKI209V1K (IIS2ICLX)

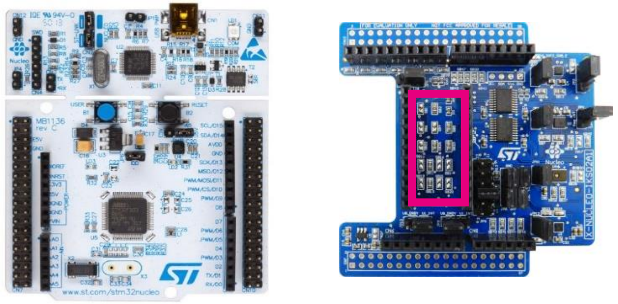
UNICO



PC Application and Software package
Unicleo-GUI
X-CUBE-MEMS1



DIL24 adapter board
STEVAL-MKI209V1K (IIS2ICLX)



STM32 Nucleo

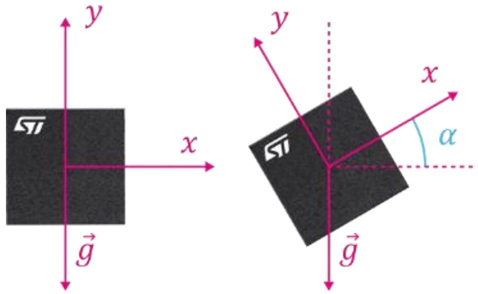
STM32 NUCLEO & Industrial Sensor expansion board
e.g., NUCLE-F401RE
X-NUCLEO-IKS02A1

life.augmented

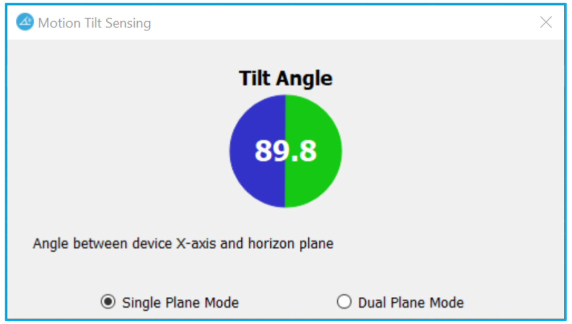
Tilt Measurement Library for 2-axis AXLs
Measurement modes

Single plane mode

- Single plane mode provides the angle of X axis with respect the horizontal plane
- The reference position is when the **X axis is in horizontal plane and Y axis is pointing up** (towards sky)

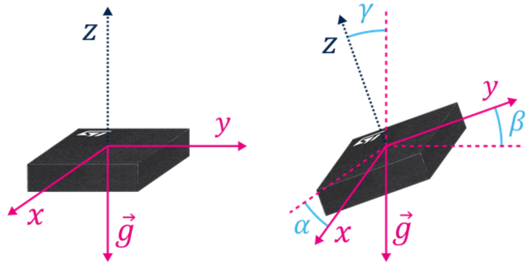


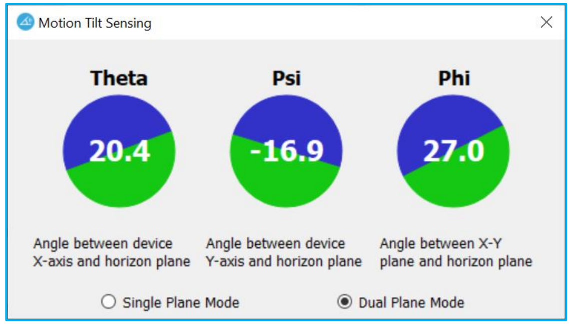
Range:
[-180°, +180°]



Dual plane mode

- This mode provides angles between the horizontal plane, X-axis (α) and Y-axis (β), and angle between vertical axis and gravity vector (γ)
- The reference position is when the **X and Y axis is in horizontal plane**





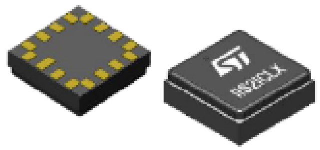
Range:
[-90°, +90°]

Summary and More Information

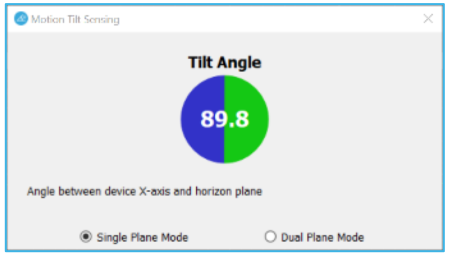
life.augmented

Get the angle right with IIS2ICLX

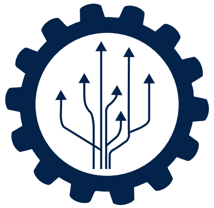
High accuracy 2-axis inclinometer for industrial applications



1 **High stability** over temperature and time



2 **MotionTL2** SW package available for 2-axis inclination measurements

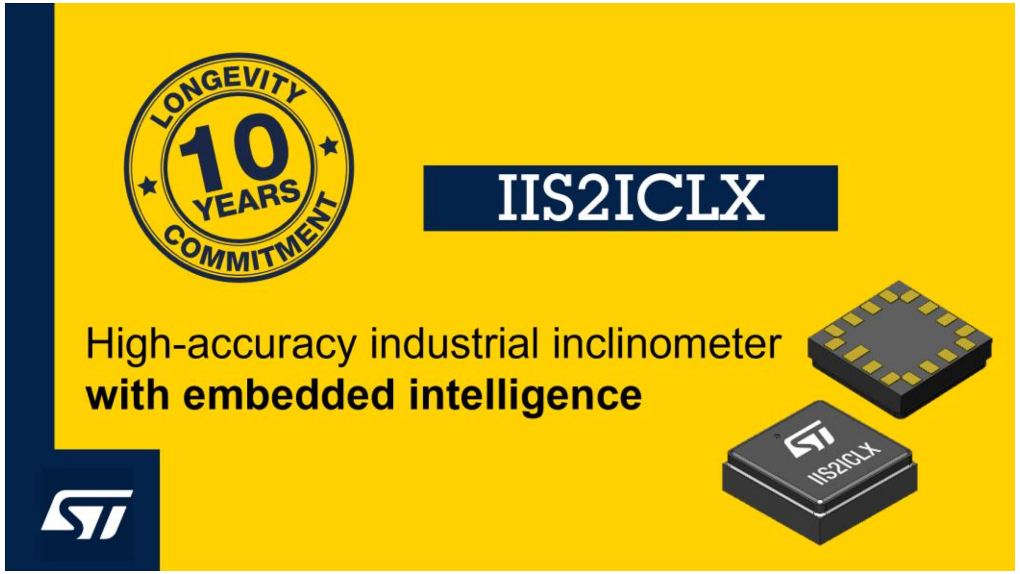


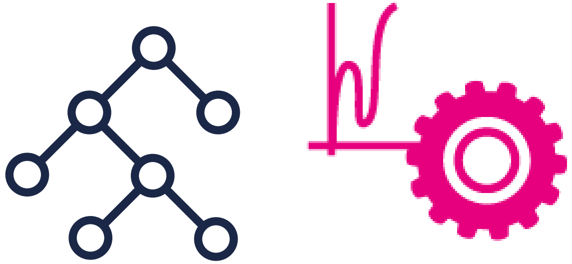
3 **MLC** inside to optimize power consumption and enable advanced functionalities

IIS2ICLX

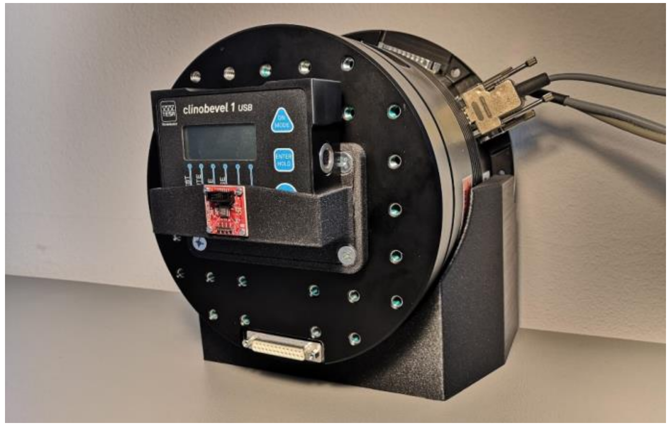
Demo on ST Booth 333 in Hall 1

Utilization of MLC for inclination measurement





- Introduction of IIS2ICLX
- Applications suitable for IIS2ICLX
- Explanation of **M**achine **L**earning **C**ore
- **MLC** for **tilt measurement**



Watch video

Search “IIS2ICLX” on YouTube or ST.com

Tilt sensing documentation

- Technical Note:
  - TN0018 – Surface Mounting Guidelines for MEMS Sensors
- Application Notes:
  - AN5551 – Precise and accurate tilt sensing in industrial applications
  - AN4508 – Parameters and calibration of a low-g 3-axis accelerometer
  - AN4509 – Tilt measurement using a low-g 3-axis accelerometer
- Design Tips:
  - DT0140 – Tilt computation using accelerometer data for inclinometer applications
  - DT0105 – 1-point or 3-point tumble sensor calibration
  - DT0053 – 6-point tumble sensor calibration
  - DT0059 – Ellipsoid or sphere fitting for sensor calibration
  - DT0076 – Compensating for accelerometer installation error

Our technology starts with You

life.augmented