Get the right angle with ST IIS2ICLX 2-axis Industrial Inclinometer

23rd of February 2021

Martin Poláček
Pasi Myllymäki
Carlo Larghi

Agenda

life.augmented

Inclinometers in Industrial applications

Pointing, levelling and stabilization

Antenna pointing, platform leveling and stabilization

Robotics and IIoT

Robotics and Industrial automation

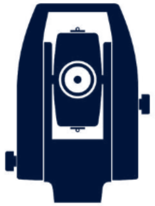
Inclinometers for industrial vehicles

High accuracy inclinometers for industrial vehicles, forklift, construction machines

Equipment Installation and monitoring

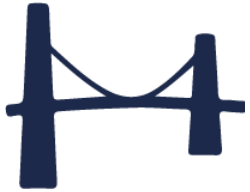
Installation and monitoring of equipment, tracker for solar panels

Leveling Instruments



Precise leveling instruments

Structural Health Monitoring

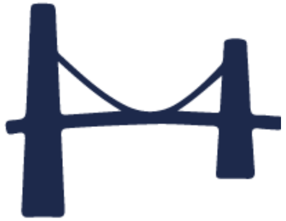


Building and infrastructure condition monitoring (inclination and low frequency vibration)

**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**

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

life.augmented

ST Sensors Longevity Program
A complete portfolio

LONGEVITY 10 YEARS COMMITMENT

Accelerometers

Inclinometers

Vibration sensors

High performance

High accuracy

High reliability

6-axis IMU + Machine Learning

Temperature sensors

High-bandwidth microphones

Tilt sensing theory

Tilt measurement with an accelerometer

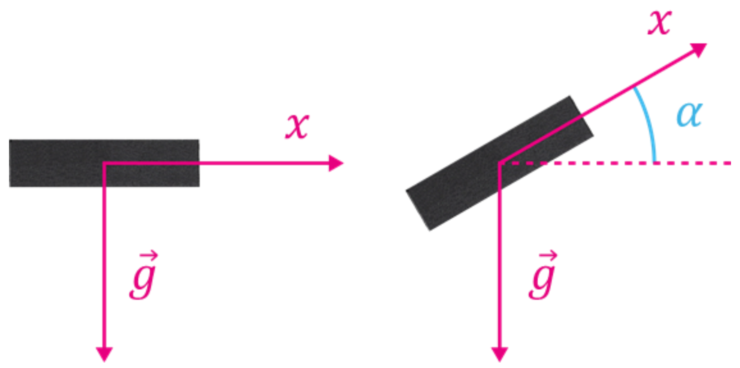
- Tilt measurement with an accelerometer is based on **projection of the Gravity vector** on its sensing axes
- An accelerometer does **not** measure **only the gravitational acceleration**, but any acceleration caused for example by:
  - Constant acceleration of the device
  - Centripetal acceleration 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

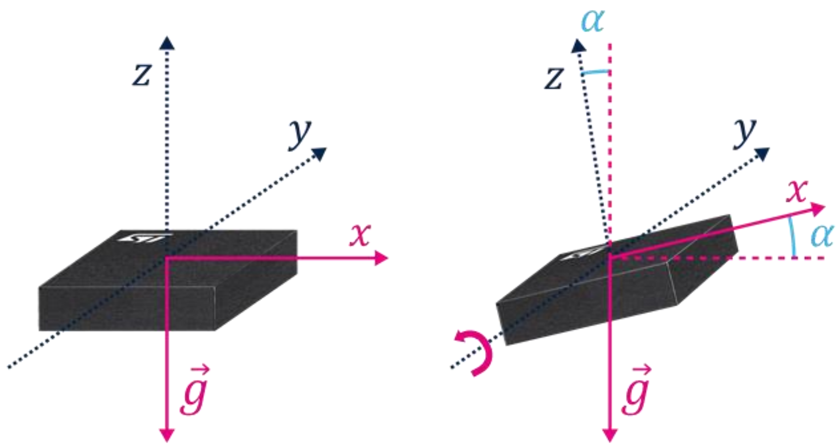
Single-axis tilt measurement

- 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



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

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

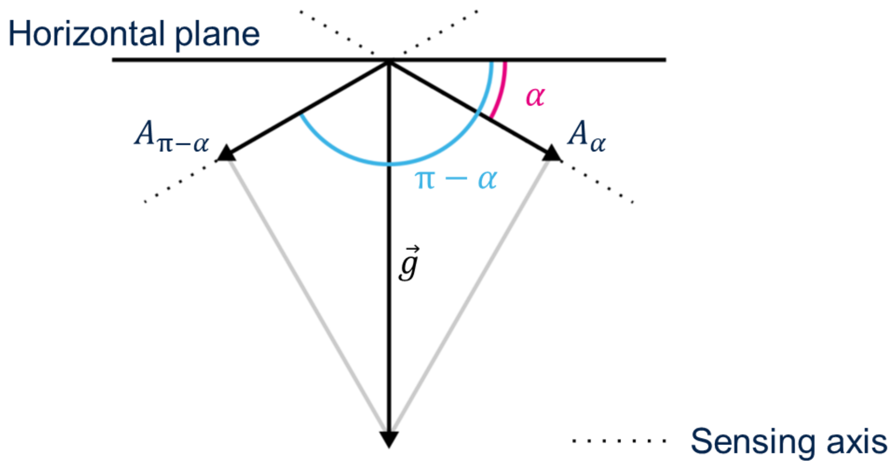


Note: $\alpha[°] = \alpha\,[rad] \cdot \left(\frac{180}{\pi}\right)$

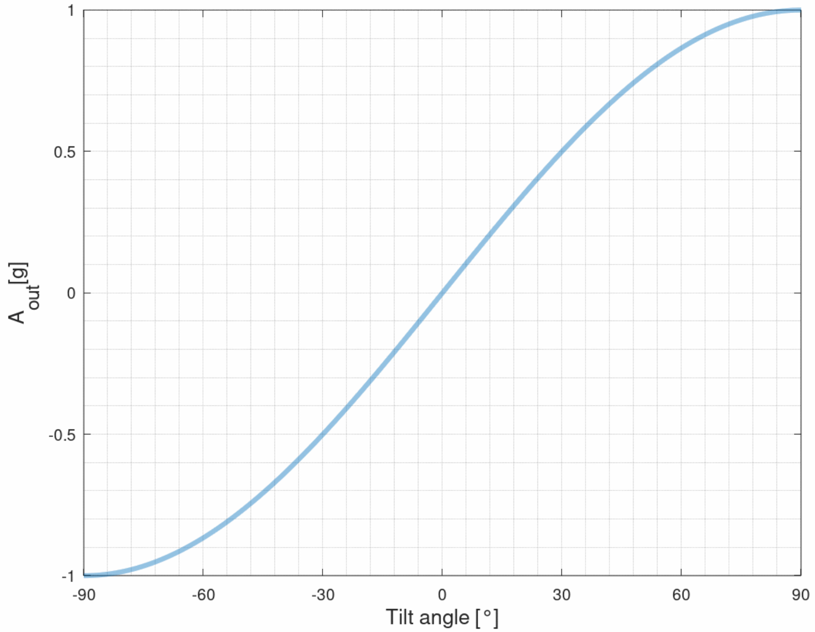
life.augmented

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



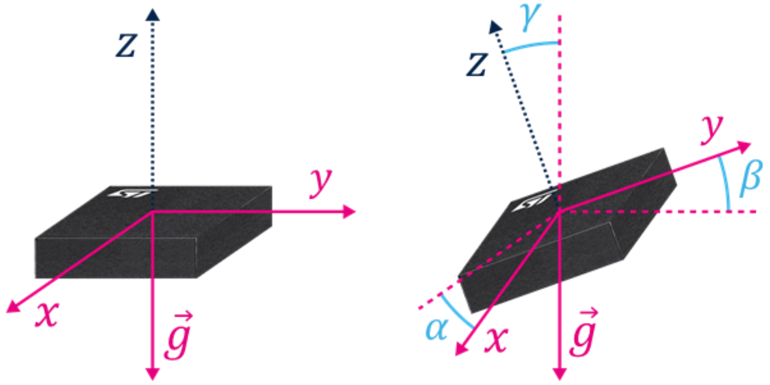
Measurement range: $\alpha = [-90°, +90°]$

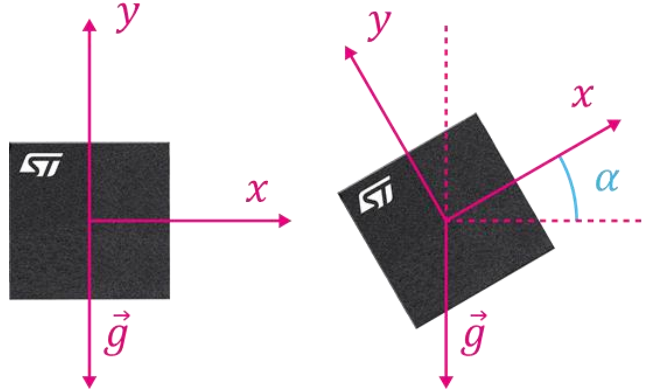


life.augmented

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:
  a) Measure tilt angles around both axes (pitch and roll)
  b) Measure a tilt angle in a complete 360° arc

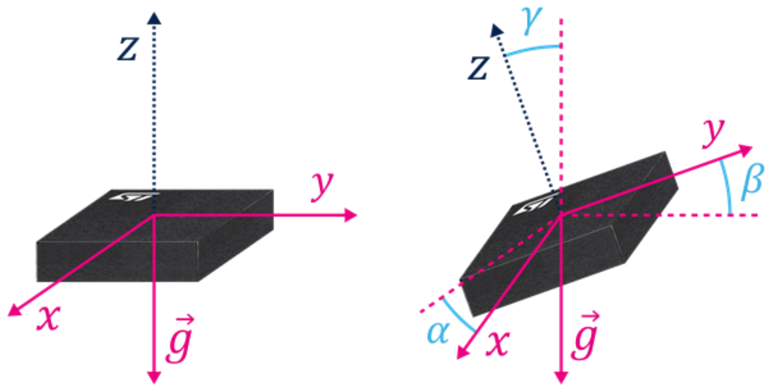




life.augmented

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
Horizontal placement

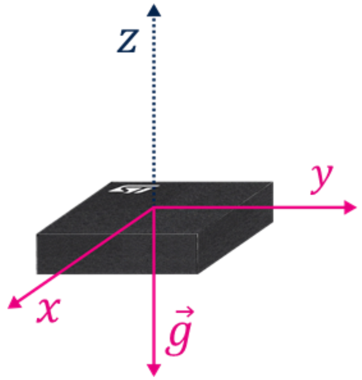
- The projected value to X and Y axis is like in the single axis case, but evaluated separately for each axis
- It is also possible to calculate the **angle between the XY plane and the horizontal plane**, γ

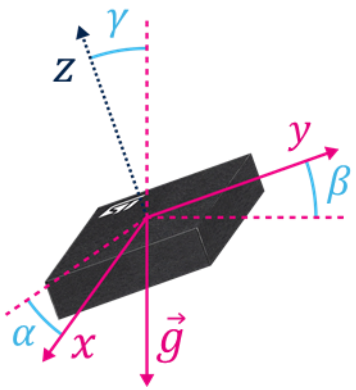
$$A_x\,[g] = 1g \cdot sin(\alpha)$$

$$A_y\,[g] = 1g \cdot sin(\beta)$$

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

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





$$\gamma[rad] = asin\left(\frac{\sqrt{A_x^2 + A_y^2}}{1g}\right)$$

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

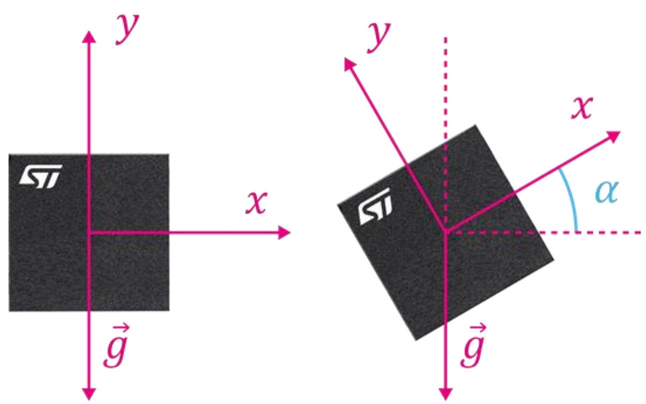
Measurement range: $\gamma = [0°, +90°]$

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:

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

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



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

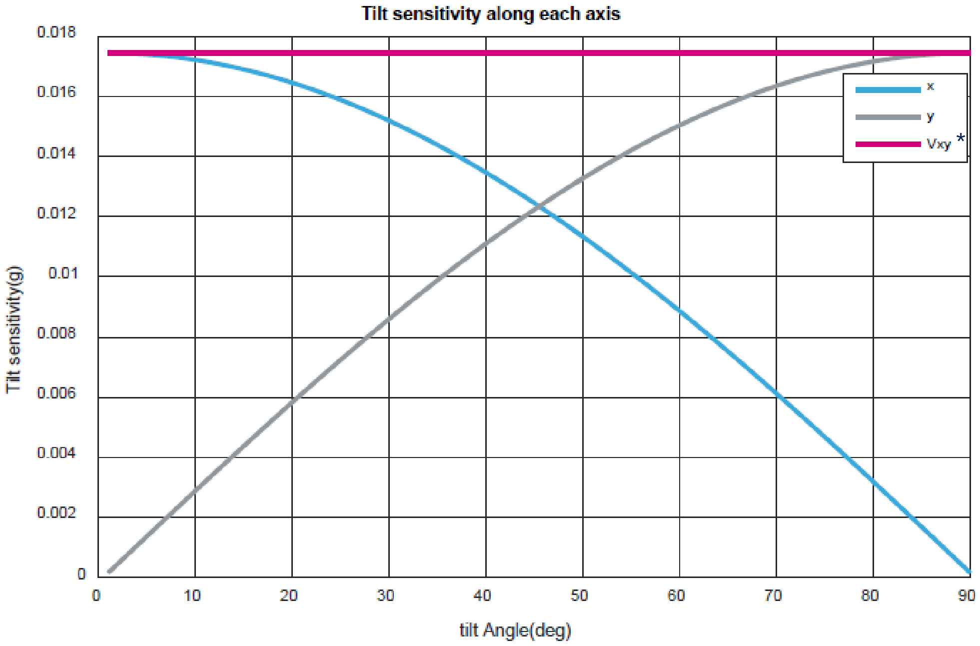
$$\boxed{\alpha[rad] = \text{atan}\left(\frac{A_x}{A_y}\right)}$$

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).

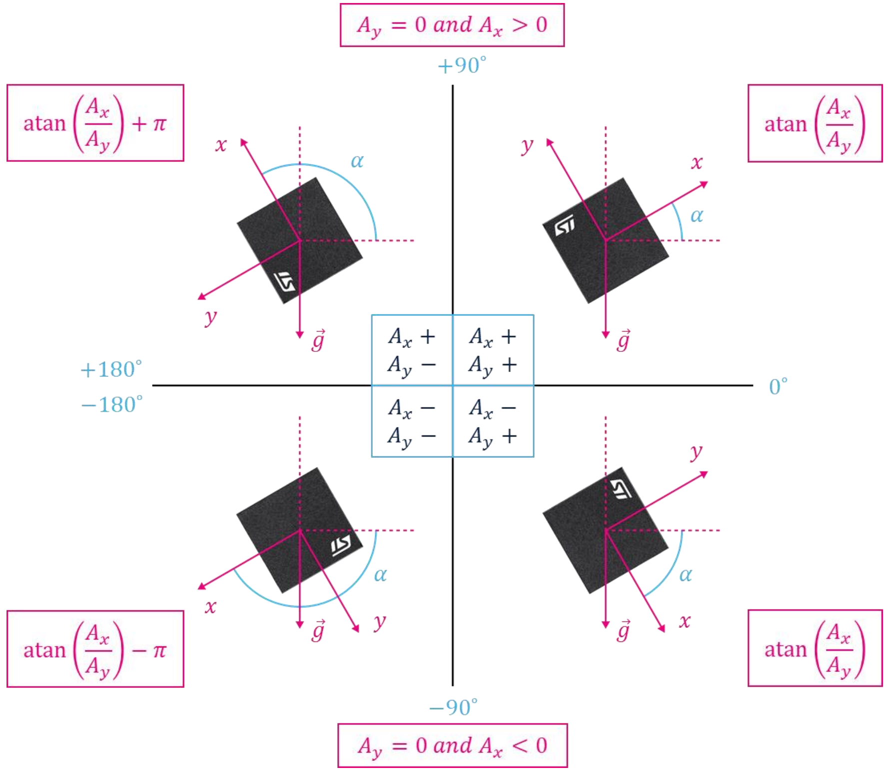
life.augmented

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

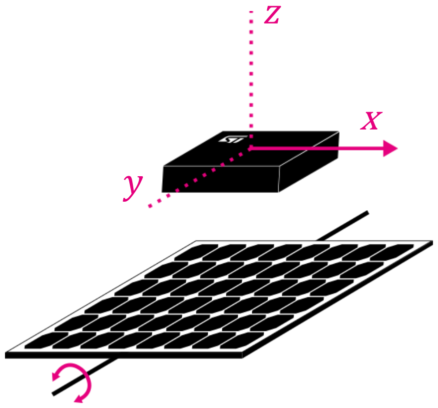


life.augmented

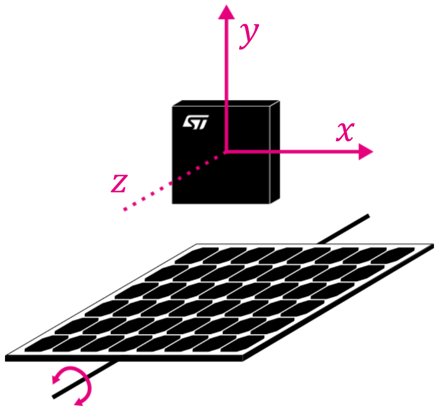
Industrial application examples

Inclinometer application examples with possible sensor placements:

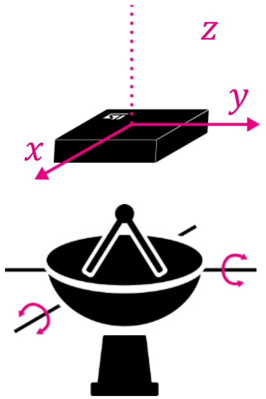
1. Tilt sensing of a solar panel that is rotated around a single axis
2. Dual-axis tilt sensing of an antenna



1-axis inclinometer



2-axis inclinometer
vertical placement



2-axis inclinometer
horizontal placement

For further application examples, please refer to:
DT0140 – Tilt computation using accelerometer data for inclinometer applications

life.augmented

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

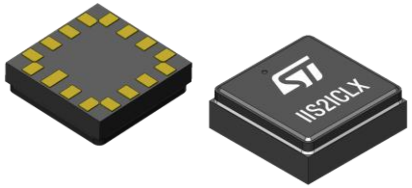
IIS2ICLX
High-accuracy 2-axis digital inclinometer

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

life.augmented

Inclinometers Comparison

	Product Name	Package [mm3]	Interface	Full Scale [g]	Zero-g level offset [mg] (max)	0g level change vs T [mg/°C] (max)	Sensitivity change vs T [%/°C] (max)	Noise density [µg/√Hz]	Current Consumption (HP mode) [mA]	Signal Bandwidth (3dB) [Hz]	ODR [Hz]	Temperature Range [°C]	Embedded Featured
STMicro electronics	**IIS2ICLX**	5 x 5 x 1.7 (Ceramic cavity LGA-16)	Digital I2C / SPI	±0.5 / ±1 / ±2 / ±3	**± 8**	**± 0.075**	**± 0.012**	**15**	0.42	25 -> 260	12.5 to 833	-40 to +105	MLC, FSM, Sensor hub, FIFO, Interrupts, wakeup, Activity/Inactivity LP/HP Filter
Comp. M	**Part Number M1**	15.6x11.3x5.1	Analog/ Digital SPI	±0.5 / ±1	**n/a**	**± 0.15**	**± 0.035**	**14**	4	8-28	n/a	-40 to +125	Direct Angle output
	Part Number M2	8.6x7.6x3.3	Digital SPI	±1.8 / ±3.6	**±20**	**± 0.1/0.15**	**±0.03**	**20**	1.2	10/40/70	2000	-40 to +125	Direct Angle output
Comp. A	**Part Number A1**	6x6x2.1	Digital SPI	±2g/±4g /±8g	**±75**	**0.15**	**(TYP) ± 0.01**	**23**	0.2	1 -> 1000	3.9 to 4000	-40 to +125	LP/HP Filter Interrupts
	Part Number A2	6x6x2.1	ANALOG	±2g/±4g	**±75**	**0.15**	**(TYP) ± 0.01**	**23**	0.15	1500	-	-40 to +125	-

life.augmented

IIS2ICLX: tilt angle error estimations

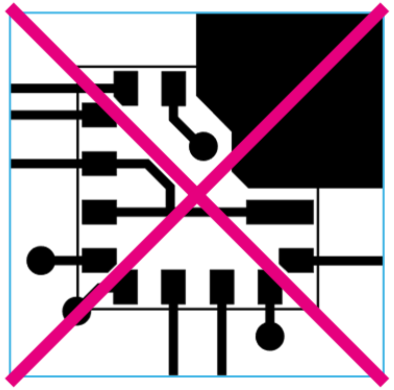
IIS2ICLX	Value	Tilt angle error
Sensitivity error	2 %	0.6 deg (using 2 axis)
Sensitivity change over life	0.7 %	0.2 deg
Sensitivity change over temperature	0.01 %/ °C	0.2 deg at max. error at 105 °C
Zero-g level offset	8 mg	0.75 deg at 30 degrees
Zero-g level offset over life	2.5	0.25 deg at 30 degrees
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	-

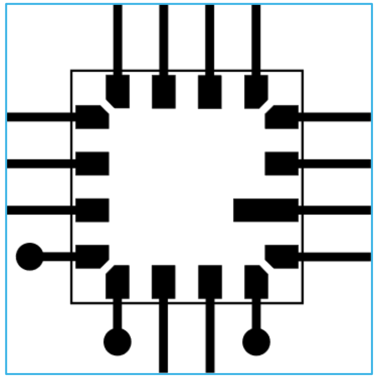
Sensitivity and Zero-g level recommended to be calibrated in production

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

PCB layout considerations

- **Do not place any structures** (such as vias, traces, planes, etc.) **on the top metal layer** beneath the sensor (on the same side of the board)
- Traces connected to pads should be as **symmetric** as possible
- **Ground plane should not be connected directly** to the footprint pads. Better to connect it through a standard trace
- Avoid placing the sensor in locations **close to hot spots** (microprocessors, graphic controllers, batteries, …), or pushbuttons

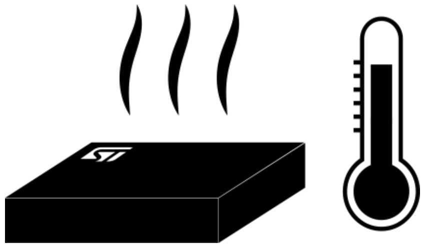




For more information, see TN0018 Surface Mounting Guidelines for MEMS Sensors

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



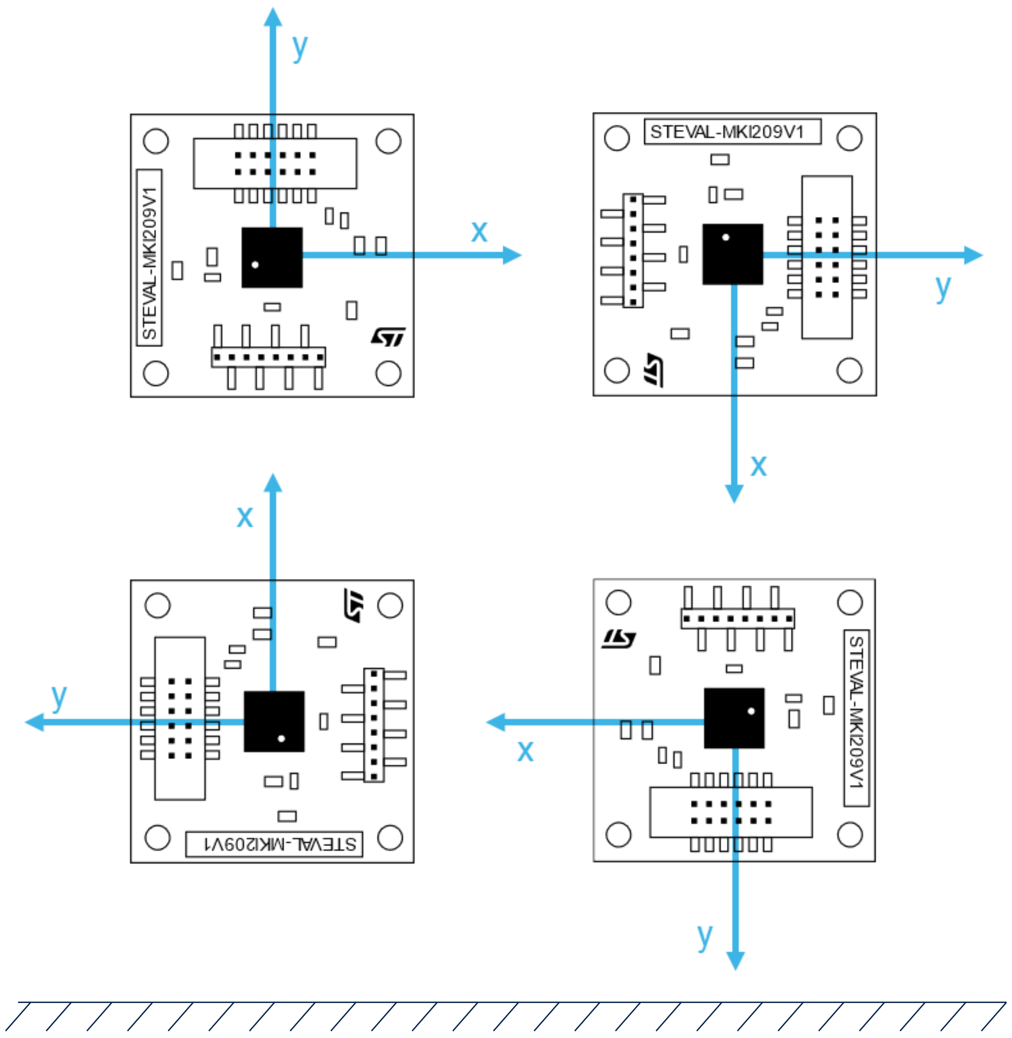
How inclinometer calibration works
Example with the IIS2ICLX

- For proper calibration, the device must be placed in **4 different directions** with respect to gravity (±X, ±Y) as shown in the picture
- The zero-g offset and sensitivity error (gain) can be then calculated from accelerometer readings, for instance through the following simple formulas:

$$Offset = \frac{A_{+1g} + A_{-1g}}{2}$$

$$Gain = \frac{A_{+1g} - A_{-1g}}{2 \times 1g}$$

The picture shows orientation of the STEVAL-MKI209V1 (IIS2ICLX adapter) board relative to the ground (side view)

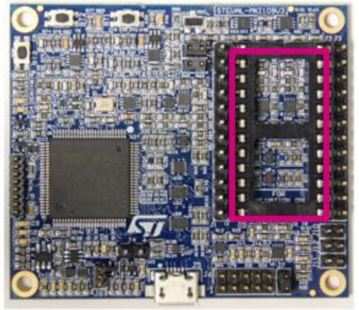


life.augmented

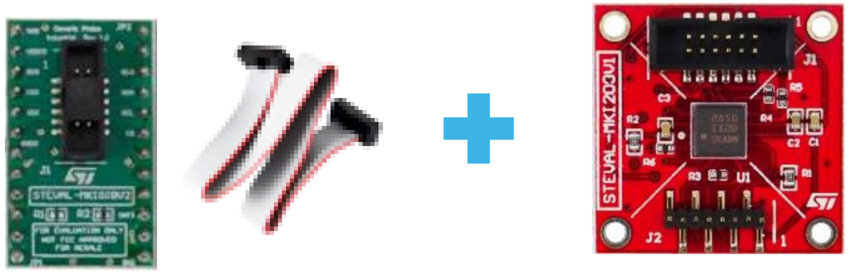
IIS2ICLX 2-axis Inclinometer:
HW & SW Tools for evaluation

Development tools for the IIS2ICLX

PC Application
Unico-GUI



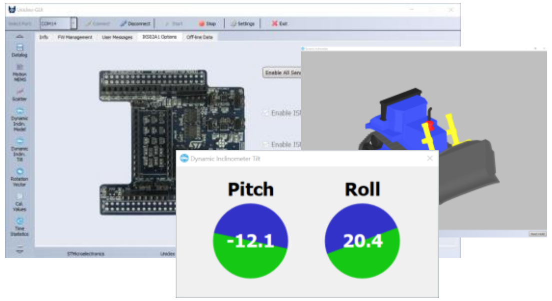
Professional MEMS motherboard
STEVAL-MKI109V3



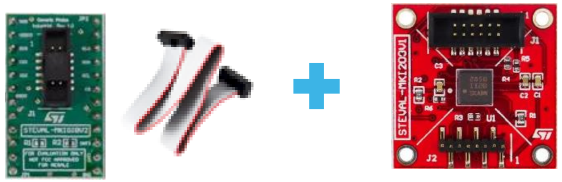
DIL24 adapter board
STEVAL-MKI209V1K (IIS2ICLX)

UNICO

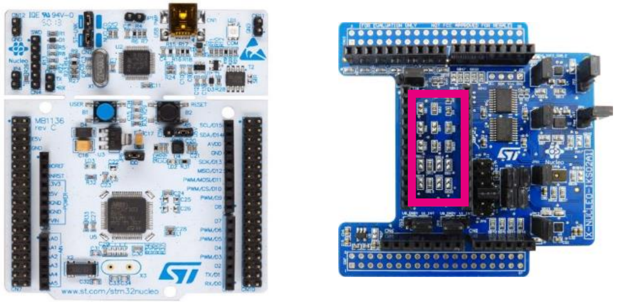
STM32 Nucleo



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



DIL24 adapter board
STEVAL-MKI209V1K (IIS2ICLX)

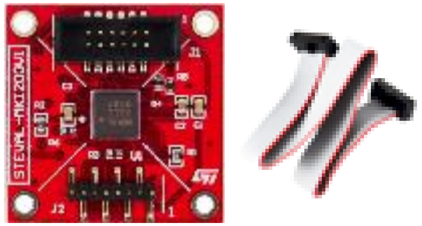


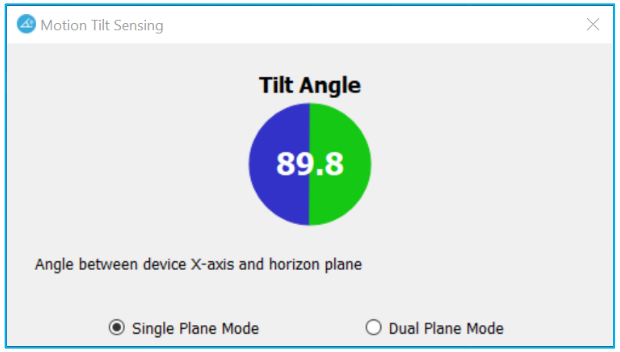
STM32 NUCLEO & Industrial Sensor expansion board
e.g., NUCLE-F401RE
X-NUCLEO-IKS02A1

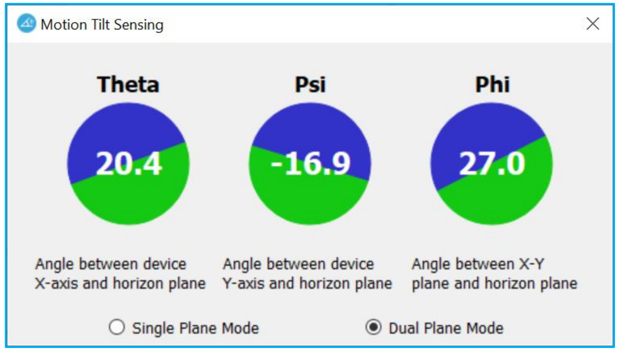
life.augmented

Tilt Measurement Library for 2-axis AXLs MotionTL2

- **MotionTL2** is a dedicated library for 2-axis accelerometers that provides real-time information about tilt angles of the user device in single or dual plane mode
- The MotionTL2 sensor fusion library features:
  - Calculation of angles according to the desired mode
  - Configuration of knobs to mitigate vibration noise
- Built especially for the IIS2ICLX
- The MotionTL2 library is part of the **X-CUBE-MEMS1** software package
  - Sample implementation is available for the STEVAL-MKI209V1K (DIL24 adapter board with the IIS2ICLX)
  - The implementation utilizes also MotionAC2 for calibration
- Available for ARM Cortex-M0+, M3, M4 and M7 architectures
- User Manual: UM2775





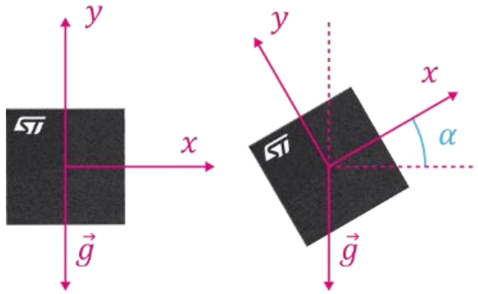


life.augmented

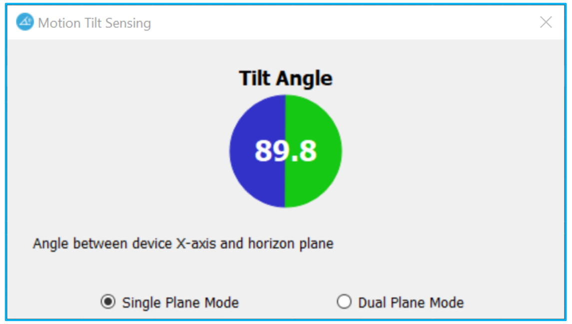
Tilt Measurement Library for 2-axis AXLs
Measurement modes

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)

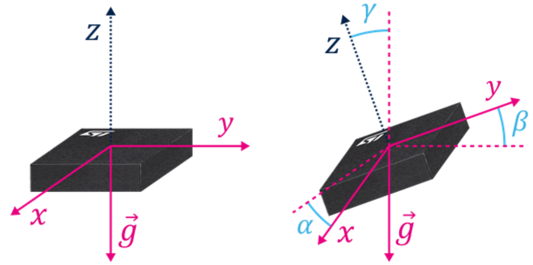


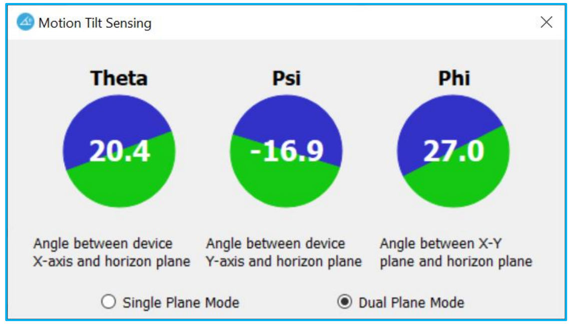
Range:
[-180°, +180°]



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°]

Tilt Measurement Library for 2-axis AXLs X-CUBE-MEMS1: Running the demo

1 Go to www.st.com

life.augmented

X-CUBE-MEMS1

Product Catalog English Login

2 Search for “X-CUBE-MEMS1”

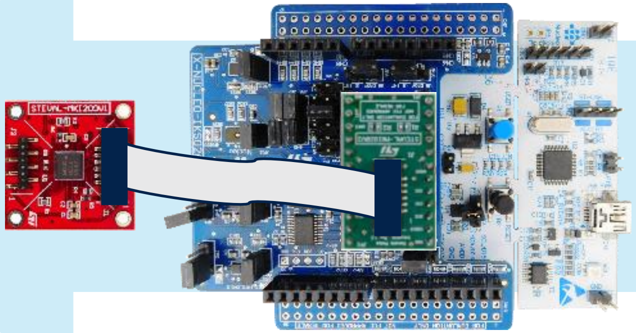
Get Software

3 Download & Unpack X-CUBE-MEMS1 package

X-CUBE-MEMS1 package structure

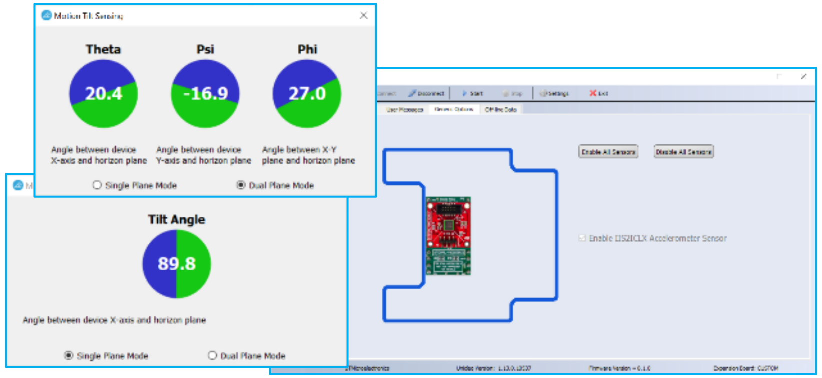
- _htmresc
- CubeMX ← Templates for CubeMX
- Documentation ← Documentation
- Drivers ← Low Level drivers
- Middlewares ← SW libraries
- Projects ← Source code examples + binaries
- Utilities ← Link to Unicleo-GUI product page
- en.DM00367782.pdf
- package.xml
- Release_Notes.html
- STMicroelectronics.X-CUBE-MEMS1.pdsc

4 Drag & Drop TiltSensing2_IIS2ICLX.bin on Nucleo drive



Computer
OSDisk (C:)
NUCLEO (F:)

TiltSensing binary file location:
STM32CubeExpansion_MEMS1_V8.1.0\Projects\STM32xxxxxx-Nucleo\Applications\CUSTOM\TiltSensing2_IIS2ICLX\Binary\



5 Run the Unicleo-GUI

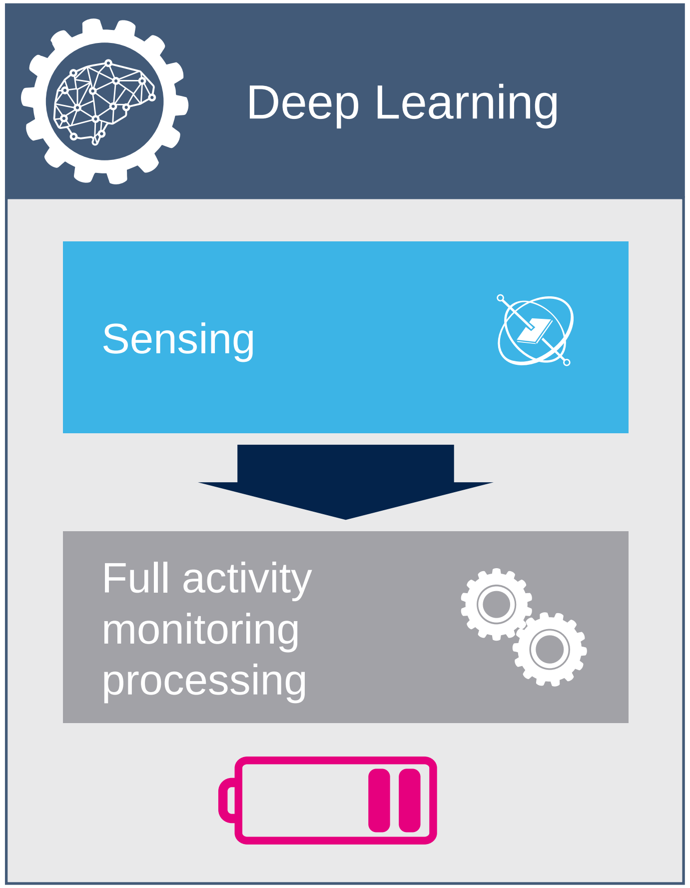
…sensor register control, raw data…

life.augmented

IIS2ICLX 2-axis Inclinometer: Machine Learning Core (MLC)

life.augmented

From low power sensor to low power system



From low power sensor to low power system

Machine Learning Core (MLC) for real edge computing enables high system flexibility

Deep Learning

Sensing

Full activity monitoring processing

Power optimization at system level

Machine Learning

Sensing
&
pre-processing

High-level processing

life.augmented

From low power sensor to low power system

Machine Learning Core (MLC) for real edge computing enables high system flexibility

Deep Learning

Sensing

Full activity monitoring processing

Power optimization at system level

Machine Learning

Sensing & **pre-processing**

High-level processing

FSM up to 16

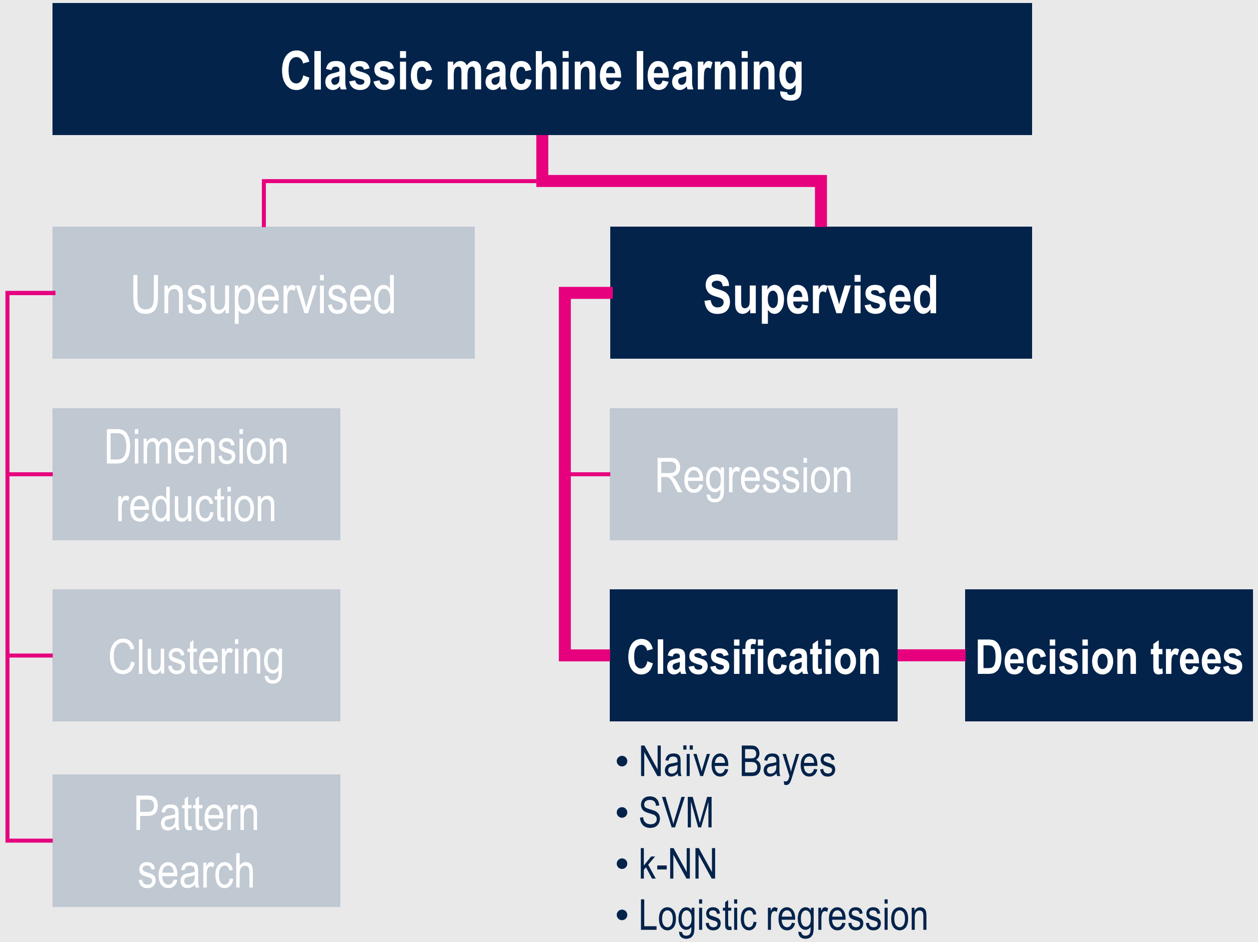
MLC up to 8

- Higher computation power
- Lower power consumption
- Cost optimized solution

This is the added value!

life.augmented

Machine Learning embedded in ST sensors



life.augmented

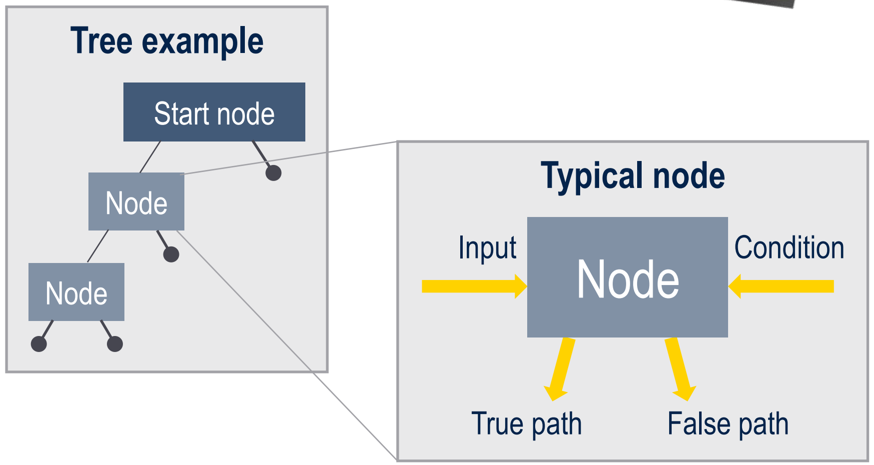
Machine Learning embedded in ST sensors

Classic machine learning

- Unsupervised
  - Dimension reduction
  - Clustering
  - Pattern search
- **Supervised**
  - Regression
  - **Classification** — **Decision trees**
    - Naïve Bayes
    - SVM
    - k-NN
    - Logistic regression

MLC is an in-sensor engine embedded in the latest products:

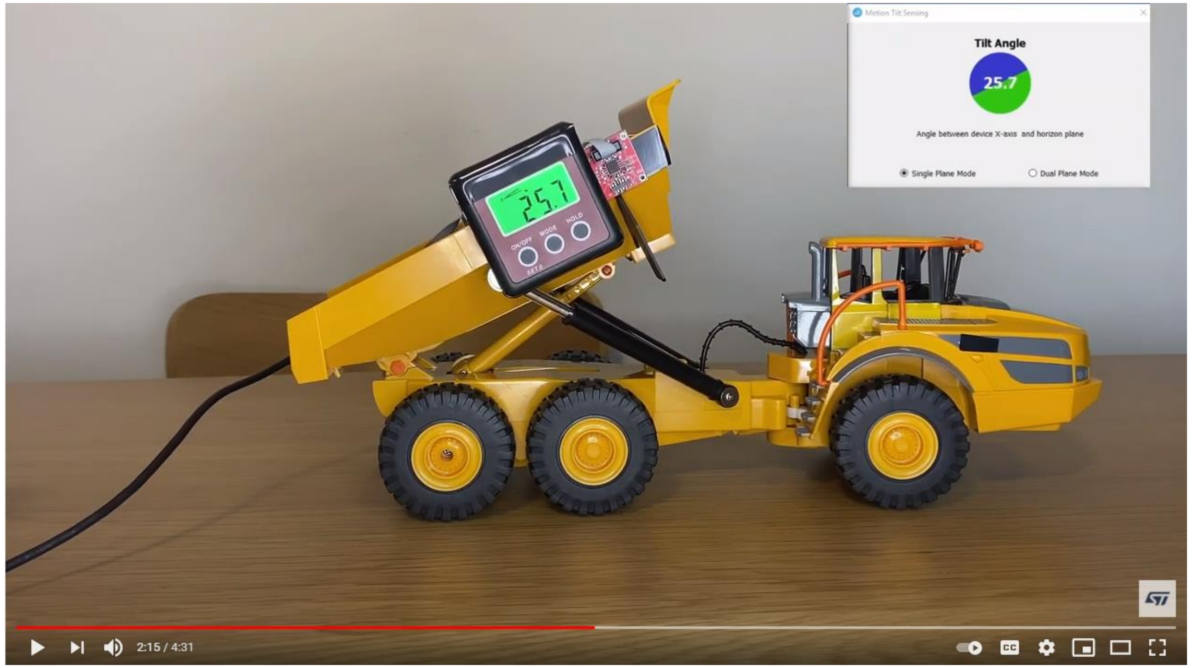
- 6x IMUs
- Inclinometer



life.augmented

Industrial tilt sensing MLC example

- “Small scale” **industrial machinery example <u>video</u> to measure tilt angle** with respect to calibrated reference sensor using IIS2ICLX Nucleo development kit, MotionTL2 algorithm and Unicleo GUI
- **MLC classification** also used for **Truck Bed “Closed/Partially Open/Open scenario”** running on MLC 1 (4=Partially Open)



IIS2ICLX with MotionTL2 vs reference tilt sensor

MLC classification of Truck Bed “Closed/Partially Open/Open”

The key steps behind sensors machine learning

Machine Learning Core configuration

Operating mode

Capture data

- Accelerometer
- Gyroscope
- External sensors

1

life.augmented

The key steps behind sensors machine learning

Machine Learning Core configuration

Operating mode

Capture data

- Accelerometer
- Gyroscope
- External sensors

1

Label data

- Filters
- Features

2

The key steps behind sensors machine learning

Machine Learning Core configuration | Operating mode

Capture data

- Accelerometer
- Gyroscope
- External sensors

1

Label data

- Filters
- Features

2

Build decision tree

- Classification
- Results

3

UNICO

WEKA MATLAB python rapidminer

Application Note AN5536
– IIS2ICLX: Machine Learning Core

life.augmented

The key steps behind sensors machine learning

Machine Learning Core configuration ❯ Operating mode

Capture data

- Accelerometer
- Gyroscope
- External sensors

1

Label data

- Filters
- Features

2

Build decision tree

- Classification
- Results

3

Embed decision tree

- DT implementation

4

UNICO

WEKA The University of Waikato MATLAB python™ rapidminer

life.augmented

The key steps behind sensors machine learning

Machine Learning Core configuration → **Operating mode**

Capture data	Label data	Build decision tree	Embed decision tree	Process new data
• Accelerometer • Gyroscope • External sensors	• Filters • Features	• Classification • Results	• DT implementation	• Real time test
1	2	3	4	5

UNICO

WEKA The University of Waikato · MATLAB · python™ · rapidminer

life.augmented

Explore MLC resources and examples

- Machine Learning Core landing page is the reference product resources and ML introduction to users:

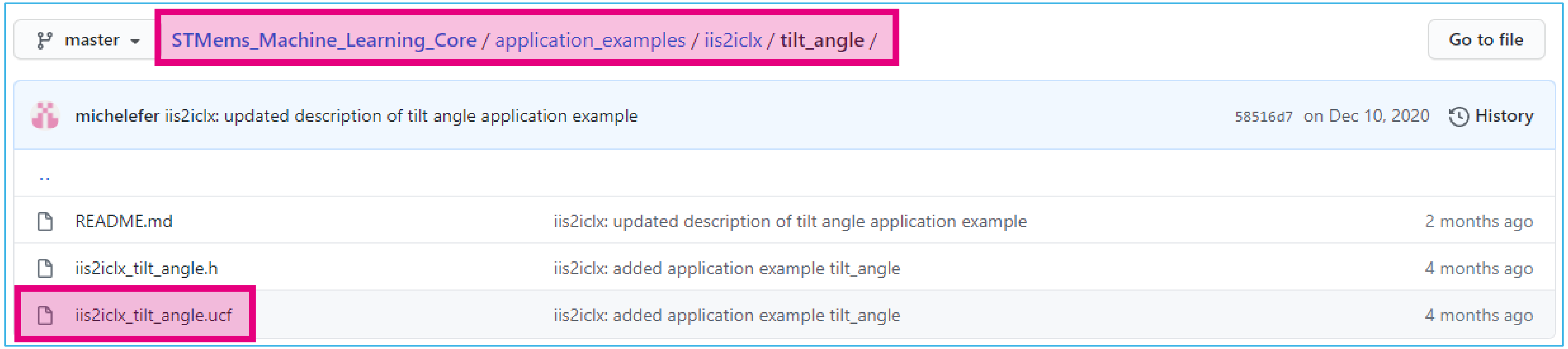
https://www.st.com/content/st_com/en/campaigns/machine-learning-core.html

- Decision tree examples are available online at the dedicated **GitHub project for Machine Learning Core**

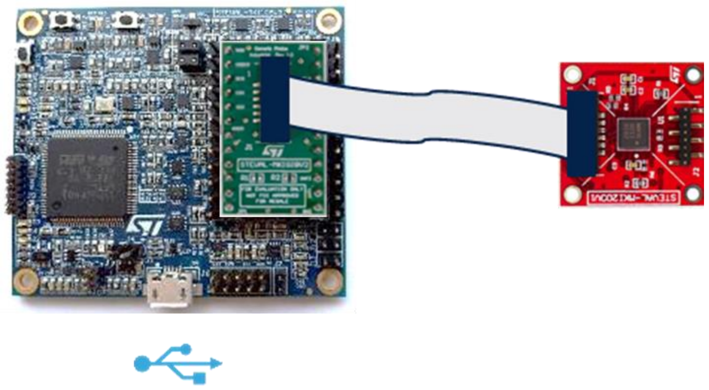
https://github.com/STMicroelectronics/STMems_Machine_Learning_Core

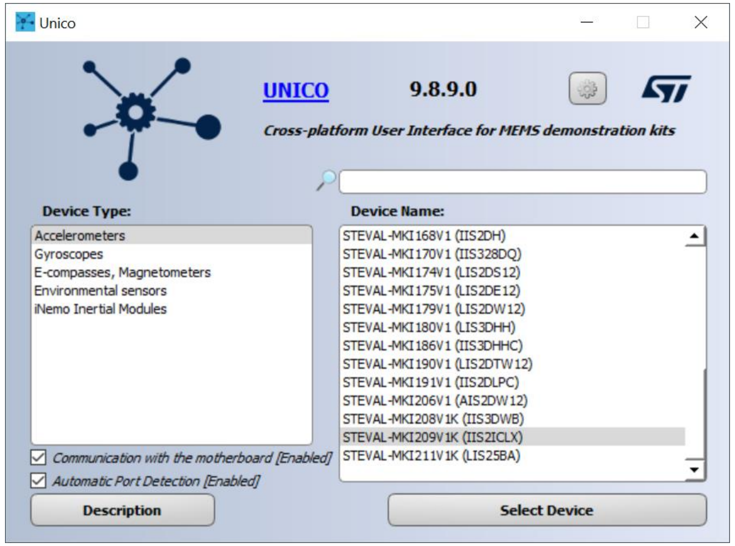
life.augmented

Tilt sensing MLC example with ProfiMEMSTool



1. Download “iis2iclx_tilt_angle.ucf” file from GitHub

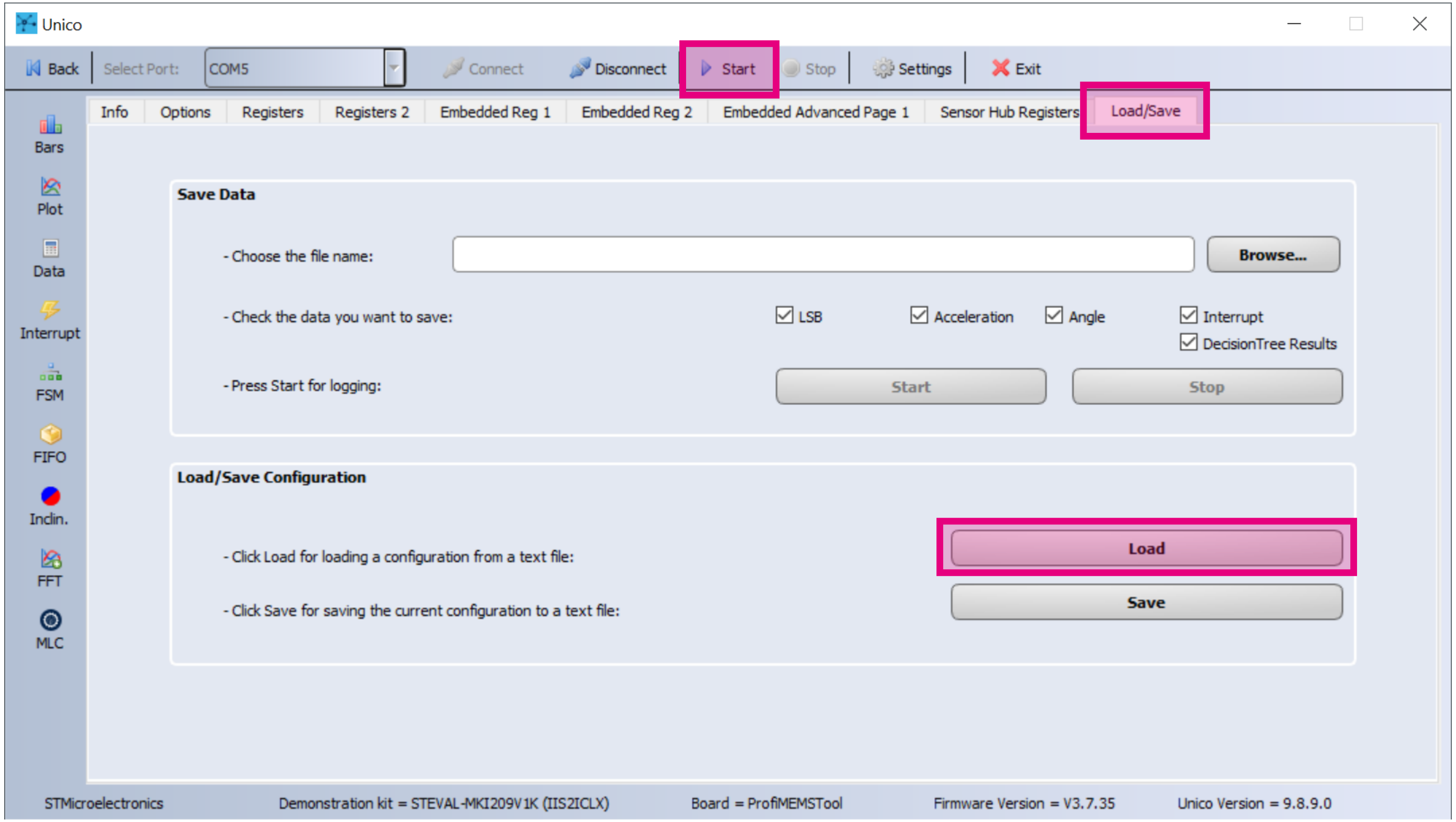




2. Connect the ProfiMEMSTool board with the DIL24 adapter board to PC using an USB cable

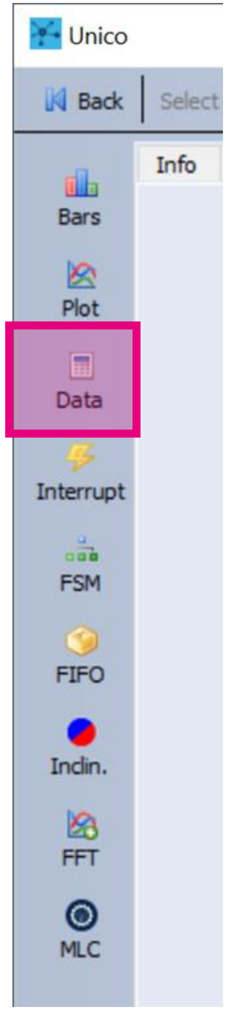
3. Run Unico-GUI and select IIS2ICLX

Tilt sensing MLC example with ProfiMEMSTool

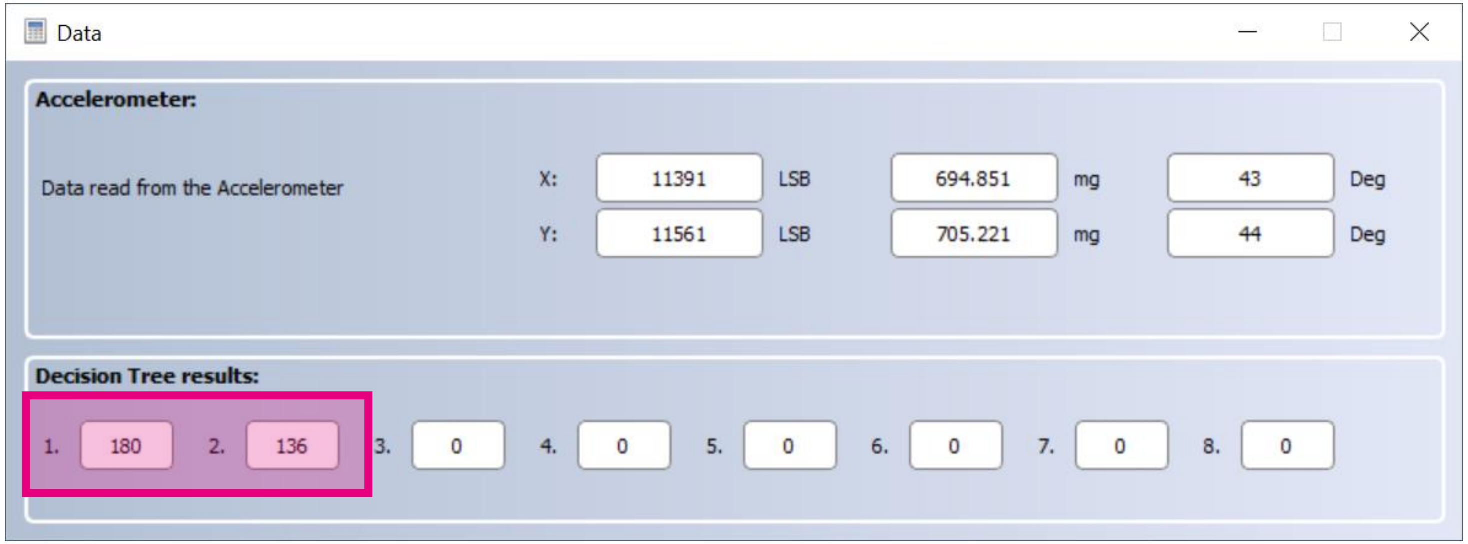


1. Go to Load/Save tab
2. Click the Load button and browse for the .ucf file (it contains the sensor & MLC configuration)
3. Click the Start button

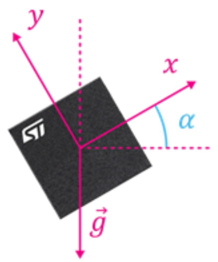
Tilt sensing MLC example with ProfiMEMSTool



1. Open the Data window from the left side panel



2. See the tilt angle in the Decision Tree results section
(The tilt angle is the sum of the outputs of the two decision trees)

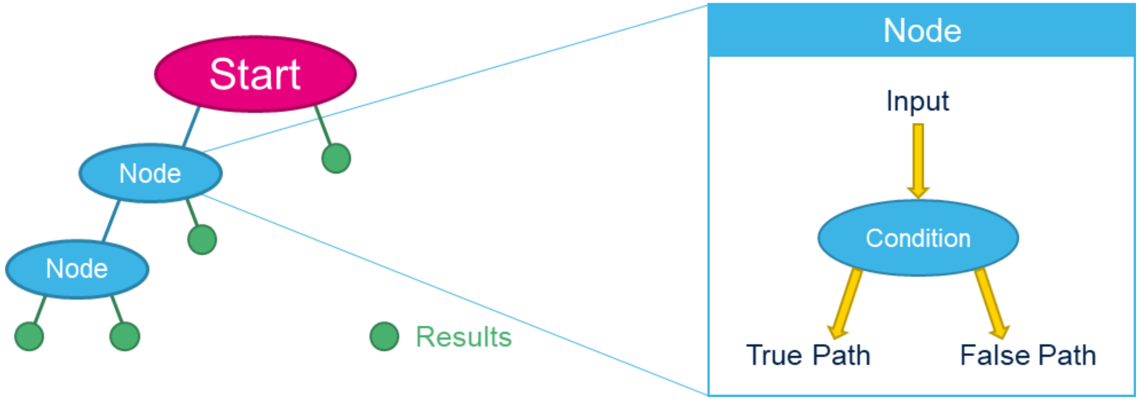


The Tilt sensing MLC example considers vertical placement.
Further information can be found on GitHub.

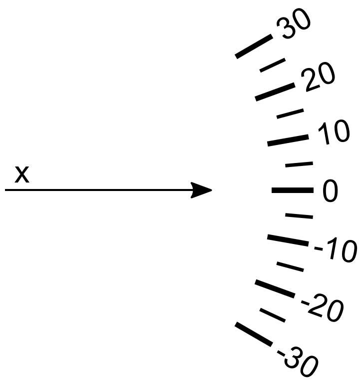
life.augmented

Tilt sensing MLC example

- Each Node of a decision tree is characterized by one «if-then-else» condition
- It is possible to create a decision tree that evaluates measured acceleration and outputs a result, that corresponds to the inclination angle
- Two solutions are available:
  a) **Single-plane low-resolution (1°)** measurement in whole 360° range (available on our GitHub)
  b) **Dual-plane (resolution: ~0.16°)** measurement in reduced angle range [-20, 20]° (on demand)



Example Decision Tree

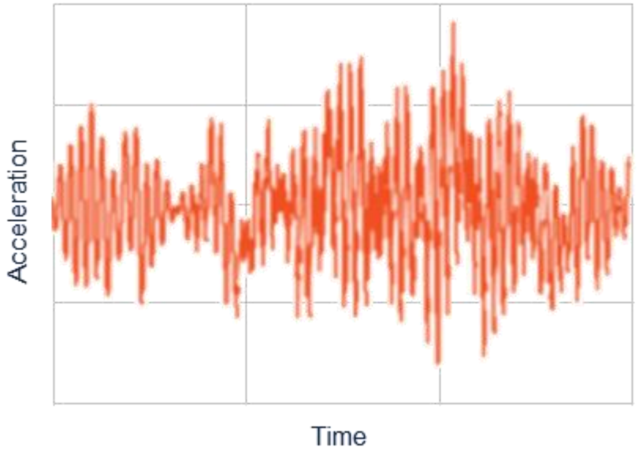


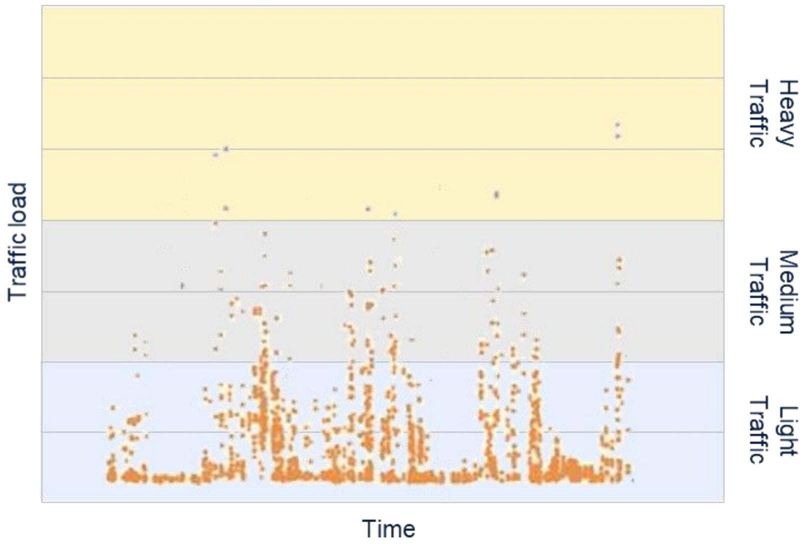
if (x <= sin(-25°)), then angle == -30°
elseif (x <= sin(-15°)), then angle == -20°
elseif (x <= sin(-5°)), then angle == -10°
elseif (x <= sin(5°)), then angle == 0°
elseif (x <= sin(15°)), then angle == 10°
elseif (x <= sin(25°)), then angle == 20°
else angle == 30°

Basic Principle of calculation

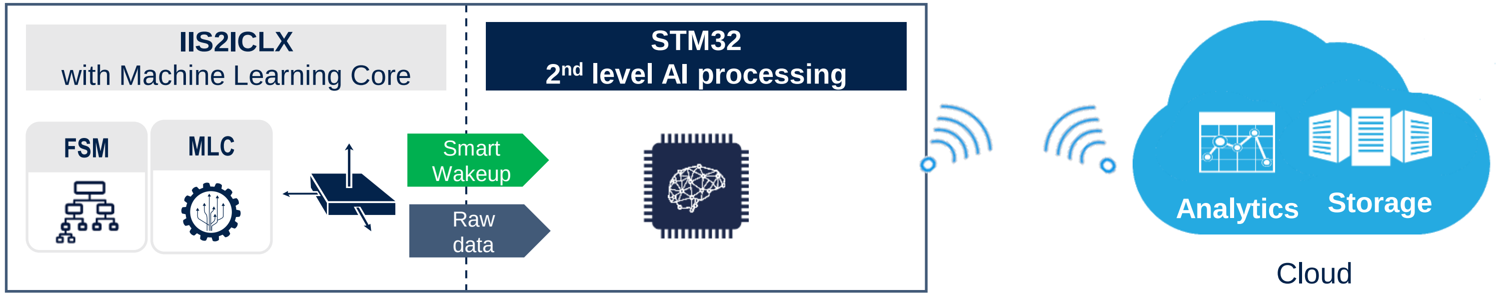
Smart Wake-up for SHM

Machine learning core embedded in **IIS2ICLX** classifies the traffic load and wakes up 2nd level processing only when relevant conditions are met





Battey powered, wireless sensor node



Edge-of-the-Edge computing

Edge computing

Not only accurate tilt for SHM Applications

Structural Health Monitoring

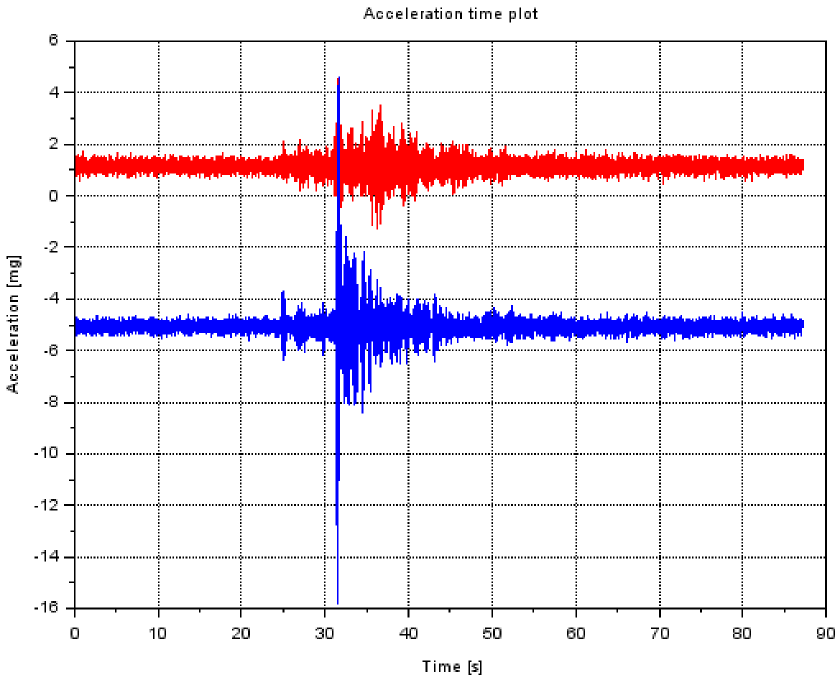
IIS2ICLX measures with **very high resolution** the **vibrations in the low frequency range (up to 260 Hz)**, which are essential for **vibration-based monitoring (VBM) of structures**, an important method of assessing the condition and the safety of vulnerable structures

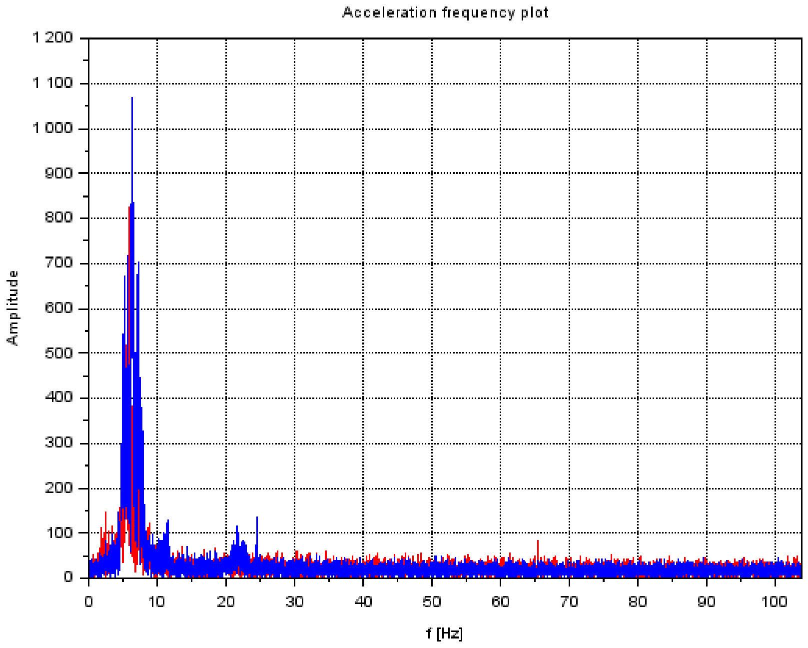
Milan earthquake
December, 17th at 16:59 CET

Magnitude **Ml 3.9**

Epicenter 4 km from Milan
Hypocenter 56 km depth

Recorded with IIS2ICLX at ST@Corenaredo (6km from the epicenter)





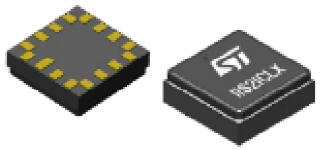
life.augmented

Summary and More Information

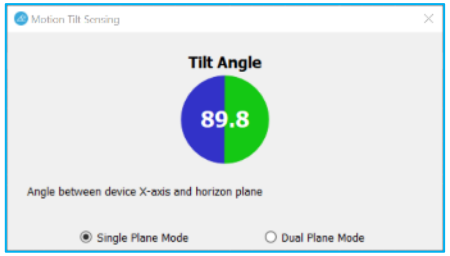
life.augmented

Get the right angle with IIS2ICLX summary

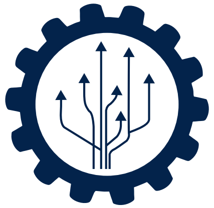
High accuracy 2-axis Inclinometer for Industrial Applications



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 available @st.com

life.augmented

Tilt sensing documentation

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

Thank you

Time for questions now!
Your questions will be also answered in our MEMS Community:
https://community.st.com/s/group/0F93W0000008QTySAM/mems-and-sensors-webinars

life.augmented