Getting started with MotionTL tilt measurement library in X-CUBE-MEMS1 expansion for STM32Cube

Introduction

The MotionTL middleware library is part of the X-CUBE-MEMS1 software and runs on STM32. It provides real-time information about the tilt angles of the user device, i.e. cell phone. The library is also able to perform accelerometer 6-position calibration.

This library is intended to work with ST MEMS only.

The algorithm is provided in static library format and is designed to be used on STM32 microcontrollers based on the ARM® Cortex®-M0+, ARM® Cortex®-M3, ARM® Cortex®-M4 or ARM® Cortex®-M7 architecture.

It is built on top of STM32Cube software technology to ease portability across different STM32 microcontrollers.

The software comes with a sample implementation running on an X-NUCLEO-IKS01A2, X-NUCLEO-IKS01A3 or X-NUCLEO-IKS02A1 expansion board on a NUCLEO-F401RE, NUCLEO-L476RG, NUCLEO-L152RE or NUCLEO-L073RZ development board.

1 Acronyms and abbreviations

Table 1. List of acronyms

Acronym	Description
API	Application programming interface
BSP	Board support package
GUI	Graphical user interface
HAL	Hardware abstraction layer
IDE	Integrated development environment

2 MotionTL middleware library in X-CUBE-MEMS1 software expansion for STM32Cube

2.1 MotionTL overview

The MotionTL library expands the functionality of the X-CUBE-MEMS1 software.

The library acquires data from the accelerometer and provides real-time tilt information with multi-mode support for 3-axis accelerometer. This library is suitable for static inclinometer where system acceleration is negligible, such as in industrial applications, leveling, satellite antennas, solar panels, and automotive.

The library is also able to perform accelerometer 6-position calibration.

The library is designed for ST MEMS only. Functionality and performance when using other MEMS sensors are not analyzed and can be significantly different from what described in the document.

A sample implementation is available for X-NUCLEO-IKS01A2, X-NUCLEO-IKS01A3 and X-NUCLEO-IKS02A1 expansion boards, mounted on a NUCLEO-F401RE, NUCLEO-L476RG, NUCLEO-L152RE or NUCLEO-L073RZ development board.

2.2 MotionTL library

Technical information fully describing the functions and parameters of the MotionTL APIs can be found in the MotionTL_Package.chm compiled HTML file located in the Documentation folder.

2.2.1 MotionTL library description

The MotionTL pedometer library manages the data acquired from the accelerometer; it features:

- calculation of pitch, roll and gravity inclination angles (Pitch-Roll-Gravity-Inclination mode)
- calculation of theta, psi and phi tilt angles (Theta-Psi-Phi mode)
- accelerometer 6-position calibration
- measurement based on the accelerometer data only
- configure knobs to mitigate vibration noise
- output: tilt angles, validity flag, expected error
- recommended sensor data sampling frequency of 100 Hz and support for all Full Scale ranges
- resources requirements:
  – Cortex-M0+: 4.1 kB of code and 0.2 kB of data memory
  – Cortex-M3: 3.6 kB of code and 0.2 kB of data memory
  – Cortex-M4: 3.3 kB of code and 0.2 kB of data memory
  – Cortex-M7: 3.3 kB of code and 0.2 kB of data memory
- available for ARM® Cortex®-M0+, ARM® Cortex®-M3 and ARM® Cortex®-M4 and ARM® Cortex®-M7 architectures

2.2.2 MotionTL APIs

The MotionTL library APIs are:

- `void MotionTL_Initialize(MTL_mcu_type_t mcu_type, const char *acc_orientation)`
  – performs MotionTL library initialization and setup of the internal mechanism
  – the CRC module in STM32 microcontroller (in RCC peripheral clock enable register) has to be enabled before using the library
- `mcu_type` is the type of MCU:
  – `MFX_CM0P_MCU_STM32` is a standard STM32 MCU
  – `MFX_CM0P_MCU_BLUE_NRG1` is BlueNRG-1
  – `MFX_CM0P_MCU_BLUE_NRG2` is BlueNRG-2
  – `MFX_CM0P_MCU_BLUE_NRG_LP` is BlueNRG-LP
- `*acc_orientation` is the reference system of the accelerometer raw data

Note: *This function must be called before using the tilt library.*

- `void MotionTL_SetKnobs(MTL_knobs_t *knobs)`
  - sets the knobs
  - the parameters for the structure type `MTL_knobs_t` are:
    - `fullscale` is the full scale of accelerometer (in g). It is recommended to set full scale >1g for the sensor. A lower full scale can be selected if the tilt variation is limited and higher resolution is required for the application.
    - `k` is the filtering coefficient. The range of k is [0.1 to ODR]. The lower value of `k` increases the filtering and removes the noise. For systems with high vibration, it is recommended to reduce the value of `k`.
    - `orn[3]` is the accelerometer data orientation string of three characters indicating the direction of each positive orientation of the reference frame used for the accelerometer data output, in the sequence x, y, z. Valid values are: n (north) or s (south), w (west) or e (east), u (up) or d (down) (see Figure 1). The `orn` is defined to bring the sensor into the X-NUCLEO-IKS01A3 frame.
    - `mode` is the operational mode where:
      - `MODE_PITCH_ROLL_GRAVITY_INCLINATION` enables angle representation in Euler angles (Roll, Pitch and Phi) form
      - `MODE_THETA_PSI_PHI` enables angle computation of theta, psi and phi angle which measure the angle individually on each axis

Note: *The API can be called after `MotionTL_Initialize()` but before `MotionTL_Update()`*

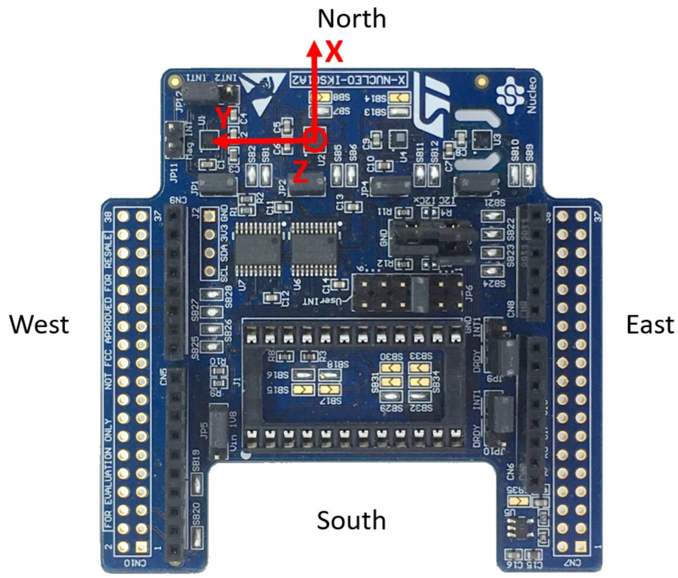
- `void MotionTL_GetKnobs(MTL_knobs_t *knobs)`
  - gets the knobs setting
  - for the parameters for the structure type `MTL_knobs_t` refer to the `MotionTL_SetKnobs()` function
- `void MotionTL_Update(MTL_input_t *data_in, uint64_t timestamp_ms, MTL_output_t *data_out)`
  - executes the tilt algorithm
  - `*data_in` parameter is a pointer to a structure with input data
  - `timestamp_ms` is the time stamp in milliseconds
  - `*data_out` parameter is a pointer to a structure with output data
  - the parameters for the structure type `MTL_input_t` are:
    - `acc_x` is the accelerometer sensor value in X axis in g
    - `acc_y` is the accelerometer sensor value in Y axis in g
    - `acc_z` is the accelerometer sensor value in Z axis in g
  - the parameters for the structure type `MTL_output_t` are:
    - `theta_3x` in Theta-Psi-Phi mode – the angle between X axis and the horizontal plane. The range of angle is [-90, 90] degrees.
    - `psi_3x` in Theta-Psi-Phi mode – the angle between Y axis and the horizontal plane. The range of angle is [-90, 90] degrees.
    - `phi_3x`in both modes – the angle between X-Y planes and the horizontal plane. The range of angle is [0, 90] degrees.
    - `roll_3x` in Pitch-Roll-Gravity-Inclination – the roll angle. The range of angle is [-180, 180] degrees.
    - `pitch_3x` in Pitch-Roll mode – the pitch angle. The range of angle is [-90, 90] degrees.
    - `err_deg` in both modes – the predicted angle error. The range of error in angle is [0, 90] degrees. The output can be used to accept/reject the tilt angle.
    - `valid` in both modes, this flag is used to show if output is valid or not. If accelerometer reading is showing high vibration or saturation at full scale, library will output ‘0’ in the valid field.

Note: *In Pitch-Roll-Gravity-Inclination mode, the `psi_3x` value represents `gravity_inclination_3x` value.*

- `uint8_t MotionTL_GetLibVersion(char *version)`
  - retrieves the library version
  - `*version` is a pointer to an array of 35 characters
  - returns the number of characters in the version string
- `void MotionTL_CalibratePosition(float cal_data[][3], uint32_t num_records, MTL_cal_position_t cal_position)`
  - calibrates accelerometer in a specific position
  - `calData` parameter is a 2D array with accelerometer data for calibration (3 axes per record)
  - `nRecords` parameter is the number of records
  - `calPosition` parameter is an enumeration of the desired position
  - the values for the enumeration type `MTL_CalPosition_t` are:
    - `X_UP`
    - `X_DOWN`
    - `Y_UP`
    - `Y_DOWN`
    - `Z_UP`
    - `Z_DOWN`
- `MTL_CalResult_tMotionTL_GetCalValues(MTL_AccCal_t *accCal)`
- – gets the calculated calibration values from the library to be used in the application
  - the return value is an enumeration of the calibration result
  - the values for the enumeration type `MTL_CalResult_t` are:
    - `CAL_PASS`: Calibration passed
    - `CAL_NONE`: Calibration not finished or not performed at all
    - `CAL_FAIL`: Calibration failed
  - `accCal` parameter is a pointer to a structure with calibration parameters
  - the parameters for the structure type `MTL_AccCal_t` are:
    - `offset` parameter is an array with calculated offset for all 3 axes
    - `gain` parameter is an array with calculated gain for all 3 axes
- `MTL_CalResult_t MotionTL_SetCalValues(MTL_AccCal_t *accCal)`
  - validates and sets the calibration values passed in the parameter
  - the return value is an enumeration of the calibration result
  - for the values for the enumeration type `MTL_CalResult_t`, see `MotionTL_GetCalValues()` function
- `void MotionTL_SetOrientation_Acc(const char *acc_orientation)`
  - this function is used to set the accelerometer data orientation
  - configuration is usually performed immediately after the `MotionTL_Initialize ()` function call
  - `*acc_orientation` parameter is a pointer to a string of three characters indicating the direction of each of the positive orientations of the reference frame used for accelerometer data output, in the sequence x, y, z. Valid values are: n (north) or s (south), w (west) or e (east), u (up) or d (down).

    As shown in the figure below, the X-NUCLEO-IKS01A2 accelerometer sensor has an NWU (x-North, y-West, z-Up), so the string is: “nwu”.

Figure 1. **Example of sensor orientations**

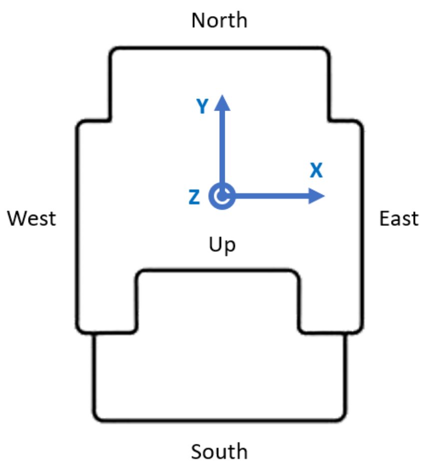


2.2.3 Orientation

The MotionTL library works with ENU orientation system, which means device X axis going to East, Y axis going to North, Z axis going Up.

Any sensor orientation is internally transformed into device ENU orientation system. For this reason the sensor orientation must be defined using `MotionTL_SetOrientation_Acc()` function. All the outputs (angels) are then calculated relative to the ENU orientation system.

Figure 2. **Device ENU orientation system**



The MotionTL library has different types of outputs angles as detailed in the following tables.

Table 2. **Pitch, Roll and Gravity Inclination output angles**

Value	Pitch	Roll	Gravity Inclination
Formula	arctan2 (-Y/Z)	arcsin (X)	arccos (Z)
Range	-180°, +180°	-90°, +90°	0, 180°
Description	Angle between Y axis and horizontal plane.	Angle between X axis and horizontal plane.	Angle between gravity vector and Z axis.
Sign	Top edge of the device going towards ground generates positive pitch.	Left edge of the device going towards ground generates positive roll.	Always positive.

Table 3. **Theta, Psi and Phi output angles**

Value	Theta	Psi	Phi
Formula	arctan (X/sqrt(Y^2+Z^2))	arctan (Y/sqrt(X^2+Z^2))	arctan (sqrt(X^2+Y^2)/Z)
Range	-90°, +90°	-90°, +90°	-90°, +90°
Description	Angle between X axis and horizontal plane.	Angle between Y axis and horizontal plane.	Angle between Z axis and gravity vector.
Sign	Left edge of the device going towards ground generates positive theta angle.	Bottom edge of the device going towards ground generates positive Psi angle.	Positive if Z axis facing up, Negative if Z axis facing down.

Note: *Calculation using tangent functions produces constant tilt sensitivity over measurement range.*

2.2.4 API flow chart

Figure 3. MotionTL API logic sequence (main program)

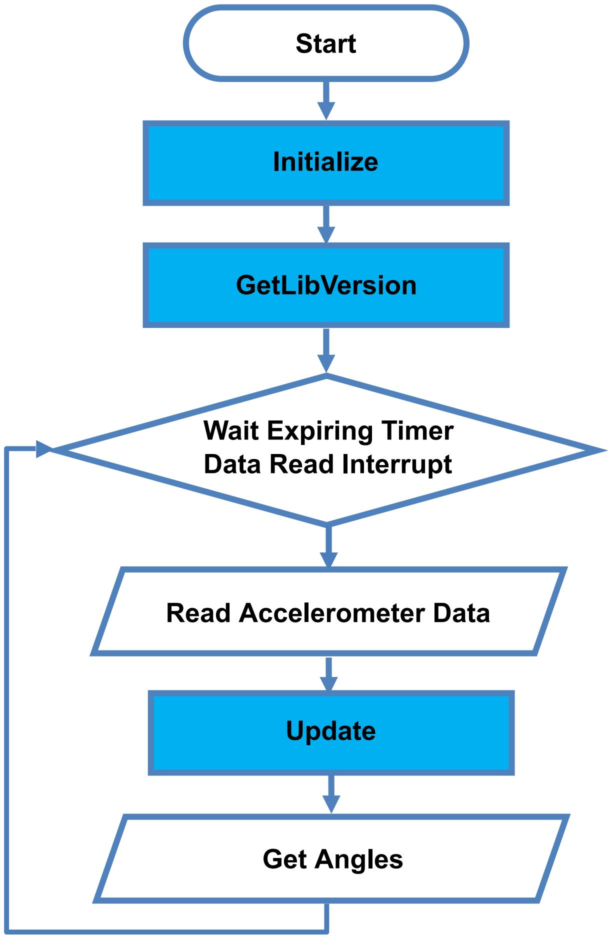
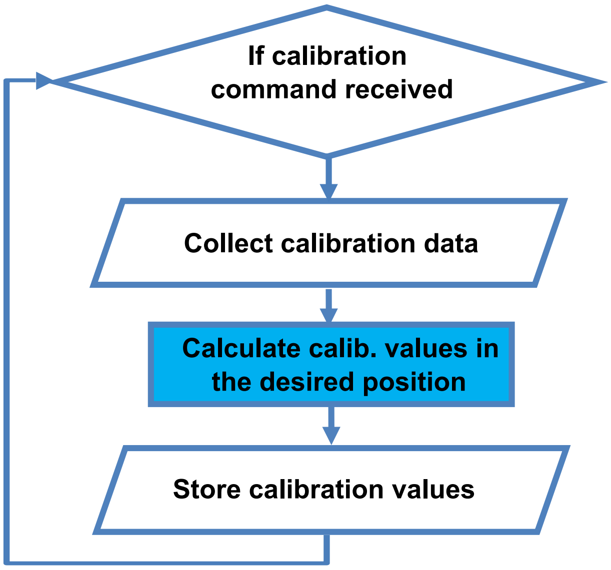


Figure 4. MotionTL API logic sequence (calibration)



2.2.5 Demo code

The following demonstration code reads data from the accelerometer sensor and gets the tilt angles.

```
[…]
#define VERSION_STR_LENG        35
[…]

/*** Initialization ***/
char lib_version[VERSION_STR_LENG];
char acc_orientation[3];

acc_orientation[0] = 'n';
acc_orientation[1] = 'w';
acc_orientation[2] = 'u';

/* Tilt API initialization function */
/* Note: Use MCU type according to target HW - in this example we use standard STM32 MCU */
MotionTL_Initialize(MTL_MCU_STM32, acc_orientation);

/* OPTIONAL */
/* Get library version */
lib_version_len = MotionTL_GetLibVersion(lib_version);

[…]

/*** Using tilt algorithm ***/
Timer_OR_DataRate_Interrupt_Handler()
{
MTL_input_t data_in;
MTL_output_t data_out;
uint64_t timestamp_ms;

/* Set the angle computation mode */
MTL_knobs_t knobs;
MotionTL_GetKnobs(&knobs);
knobs.mode = MODE_THETA_PSI_PHI;
MotionTL_SetKnobs(&knobs);

/* Get acceleration X/Y/Z in g */
MEMS_Read_AccValue(&data_in.acc_x, &data_in.acc_y, &data_in.acc_z);

/* Get timestamp in ms */
timestamp_ms = get_time_ms();

/* Run tilt sensing algorithm */
MotionTL_Update(&data_in, timestamp_ms, &data_out);
}
```

2.2.6 Algorithm performance

Table 4. Cortex -M4 and Cortex-M3: elapsed time (µs) algorithm

Cortex-M4 STM32F401RE at 84 MHz									Cortex-M3 STM32L152RE at 32 MHz								
STM32CubeIDE 1.2.0			IAR EWARM 8.32.3			Keil µVision 5.27			STM32CubeIDE 1.2.0			IAR EWARM 8.32.3			Keil µVision 5.27		
Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
80	159	163	104	104	162	104	300	303	514	571	584	373	375	575	375	967	974

Table 5. **Cortex -M0+ and Cortex-M7: elapsed time (µs) algorithm**

Cortex-M0+ STM32L073RZ at 32 MHz									Cortex-M7 STM32F767ZI at 96 MHz								
STM32CubeIDE 1.2.0			IAR EWARM 8.32.3			Keil µVision 5.27			STM32CubeIDE 1.2.0			IAR EWARM 8.32.3			Keil µVision 5.27		
Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
233	1719	1744	856	860	1727	858	2607	2619	27	28	28	17	18	18	29	30	31

2.3 Sample application

The MotionTL middleware can be easily manipulated to build user applications; a sample application is provided in the Application folder.

It is designed to run on a NUCLEO-F401RE, NUCLEO-L476RG, NUCLEO-L152RE or NUCLEO-L073RZ development board connected to an X-NUCLEO-IKS01A2, X-NUCLEO-IKS01A3 or X-NUCLEO-IKS02A1 expansion board.

The tilt sensing algorithm only uses data from the accelerometer. It detects and provides real-time information about the tilt angles of the user device. The library is also able to perform accelerometer 6-position calibration if required. The data can be displayed through a GUI.

A USB cable connection is required to monitor real-time data. This allows the user to display in real-time calculated tilt angles, accelerometer data, time stamp and eventually other sensor data using the Unicleo-GUI.

After pressing the **Tilt Calibrate** button in the Unicleo-GUI, the user is asked to hold the device still in each of the six positions while the calibration data is collected. Then the calibration parameters (offset and gain for all 3 axes) are calculated and sent to the Unicleo-GUI.

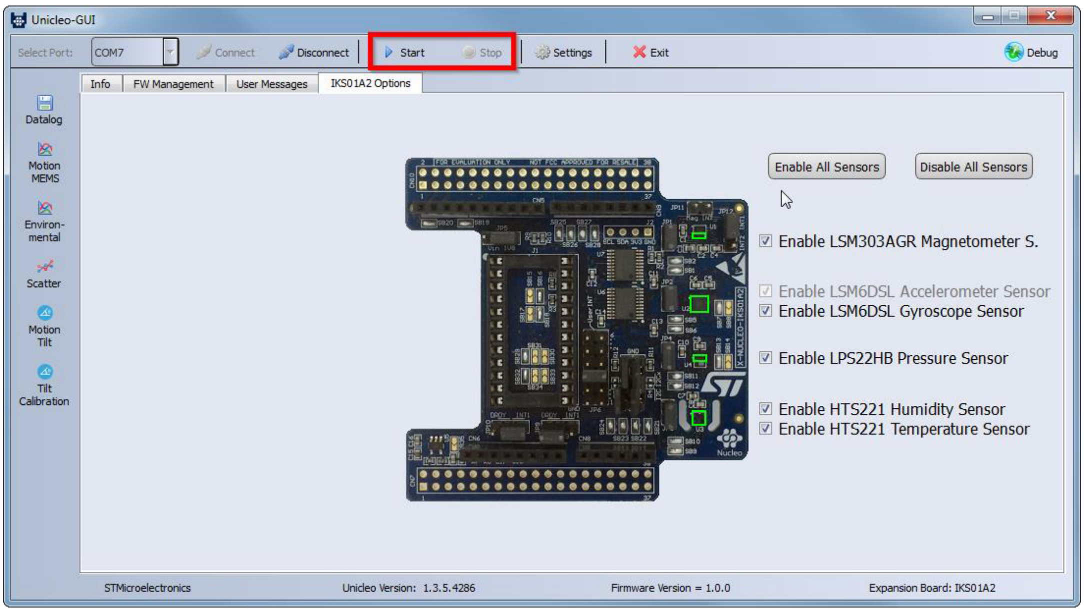
2.4 Unicleo-GUI application

The sample application uses the Windows Unicleo-GUI utility, which can be downloaded from www.st.com.

Step 1. Ensure that the necessary drivers are installed and the STM32 Nucleo board with appropriate expansion board is connected to the PC.

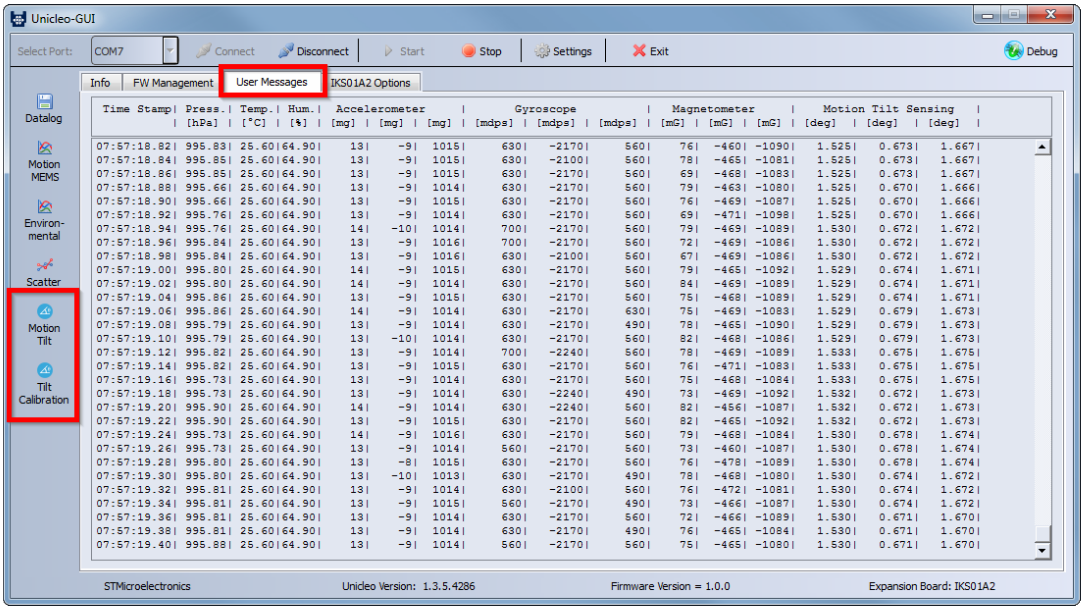
Step 2. Launch the Unicleo-GUI application to open the main application window.
If an STM32 Nucleo board with supported firmware is connected to the PC, it is automatically detected and the appropriate COM port is opened.

Figure 5. **Unicleo main window**



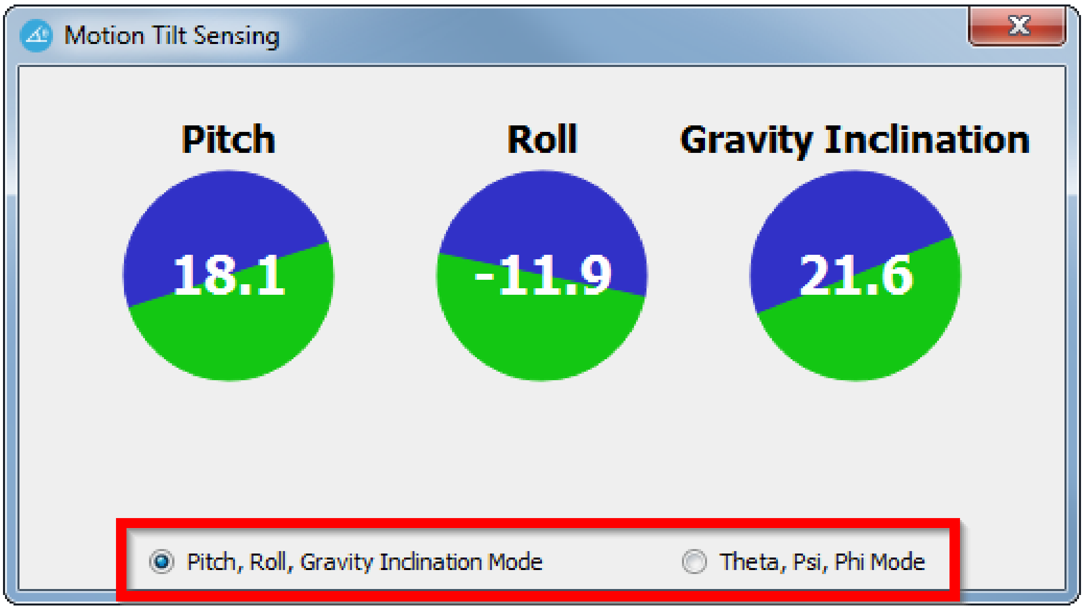
Step 3. Start and stop data streaming by using the appropriate buttons on the vertical tool bar.
The data coming from the connected sensor can be viewed in the User Messages tab.

Figure 6. User Messages tab



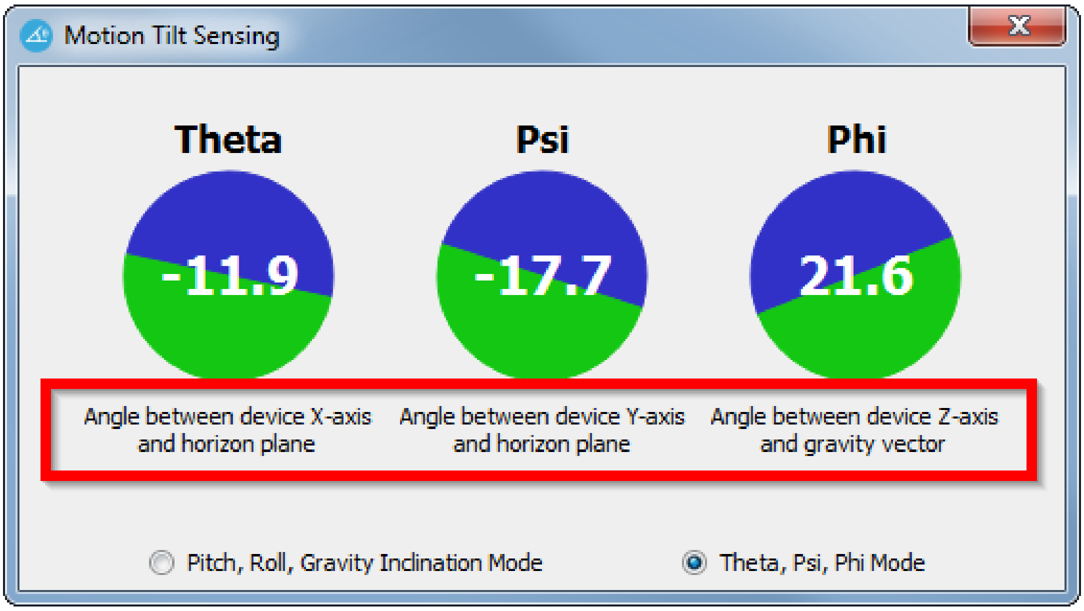
Step 4. Click on the Motion Tilt icon in the vertical tool bar to open the dedicated application window.

Figure 7. **Motion Tilt Sensing window 1**



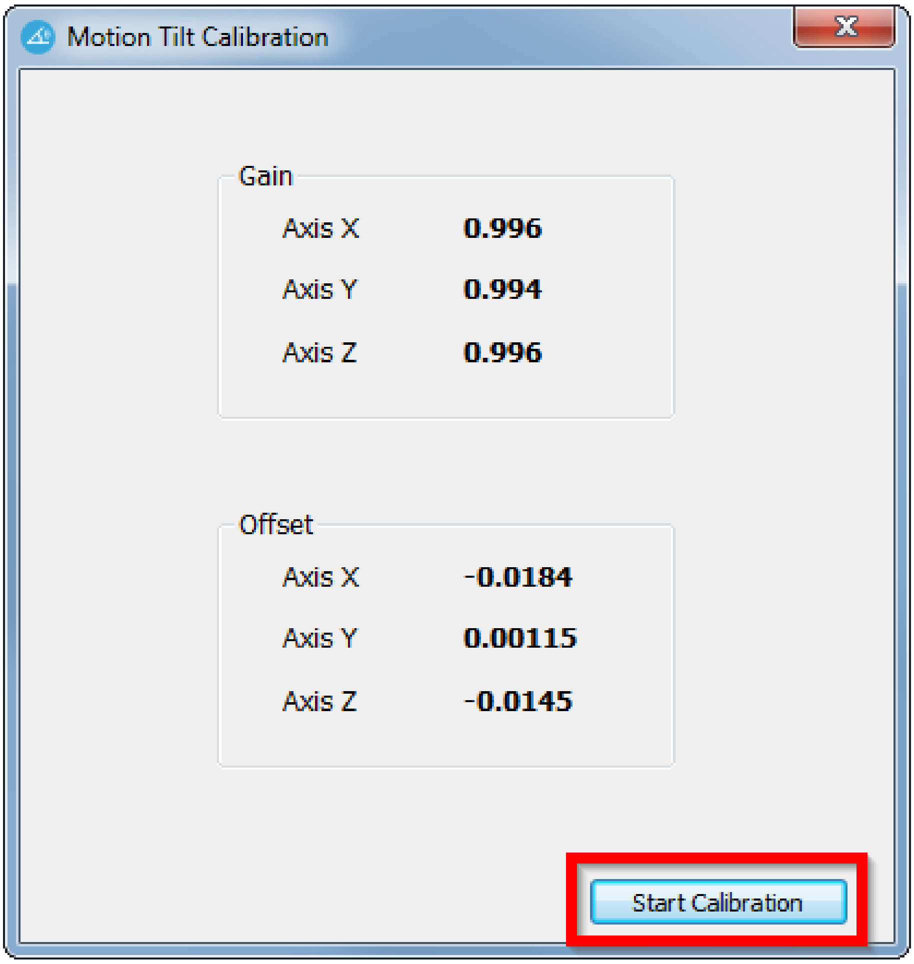
You can switch between two angle modes. In the first mode the Pitch, Roll and Gravity Inclination angles are displayed, in the second mode the Theta, Psi and Phi angles are displayed. The meaning of the angles in the second mode is displayed right below each indicator:

Figure 8. **Motion Tilt Sensing window 2**



Step 5. Click on the Tilt Calibration icon in the vertical toolbar to open the dedicated application window

Figure 9. Motion Tilt calibration window 1



This window first shows currently used calibration values calculated and stored during the previous calibration or default values if the calibration has never been performed.

You can start a new calibration by clicking the Start button:

a. put the device in the first calibration position as displayed in the picture that shows up (see Figure 8. Motion Tilt Sensing window 2)
b. click Next and hold the device still until the picture changes to another calibration position
c. repeat these steps for all 6 calibration positions.

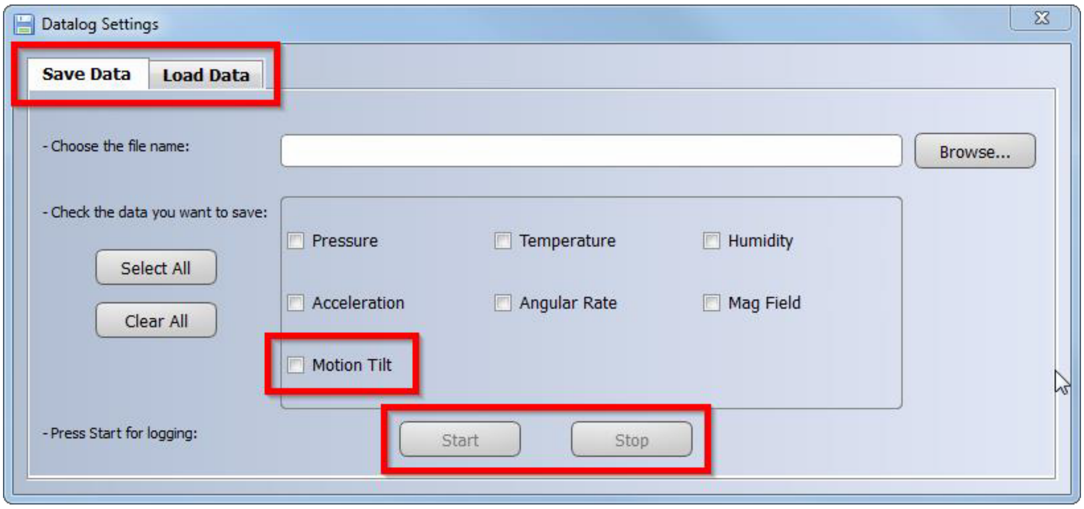
The information about the estimated time necessary for taking all calibration data in the current position is also displayed. Once the last position is calibrated, the new calibration parameters are calculated and displayed in the window (see Figure 7. Motion Tilt Sensing window 1).

Figure 10. **Motion Tilt calibration window 2**

Step 6. Click on the Datalog icon in the vertical tool bar to open the datalog configuration window: you can select which sensor and activity data to save in files. You can start or stop saving by clicking on the corresponding button.

You can also load the previously stored data.

Figure 11. **Datalog window**



3 References

All of the following resources are freely available on www.st.com.

1. UM1859: Getting started with the X-CUBE-MEMS1 motion MEMS and environmental sensor software expansion for STM32Cube
2. UM1724: STM32 Nucleo-64 boards (MB1136)
3. UM2128: Getting started with Unicleo-GUI for motion MEMS and environmental sensor software expansion for STM32Cube

Revision history

Table 6. Document revision history

Date	Version	Changes
22-Sep-2017	1	Initial release.
25-Jan-2018	2	Added references to NUCLEO-L152RE development board and Section 2.2.5 Algorithm performance.
21-Mar-2018	3	Updated Introduction and Section 2.1 MotionTL overview.
23-Oct-2018	4	Removed references to X-NUCLEO-IKS01A1 throughout document. Updated Figure 1. Example of sensor orientations and Section 2.2.5 Demo code. Added Section 2.2.3 Orientation.
20-Nov-2018	5	Added Table 5. Cortex -M0+: elapsed time (µs) algorithm. Added references to ARM® Cortex®-M0+ and NUCLEO-L073RZ development board.
21-Feb-2019	6	Updated Table 4. Cortex -M4 and Cortex-M3: elapsed time (µs) algorithm and Table 5. Cortex -M0+: elapsed time (µs) algorithm. Added X-NUCLEO-IKS01A3 expansion board compatibility information.
25-Mar-2020	7	Updated Introduction, Section 1.1 MotionTL library description and Section 2.2.6 Algorithm performance. Added ARM Cortex-M7 architecture compatibility information.
07-Apr-2021	8	Updated Introduction, Section 2.1 MotionTL overview, Section 2.2.1 MotionTL library description, Section 2.2.2 MotionTL APIs, Section 2.2.4 API flow chart, Section 2.2.5 Demo code and Section 2.3 Sample application. Added X-NUCLEO-IKS02A1 expansion board compatibility information.

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