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Embedded Motion Driver 5.1.1 Tutorial

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TABLE OF CONTENTS

1. Revision History

Revision Date	Revision	Description
12/19/2012	1.0	Document created

2. Purpose

Motion Driver is a sensor driver layer that easily configures and leverages the on board Digital Motion Processor (DMP) capabilities of InvenSense's Motion Tracking devices. Motion Driver is a subset of the Embedded MotionApps software that enables easier porting to multiple MCU architectures. This document illustrates the practical usage of the Motion Driver library. The included tutorial is written for compatibility with the MSP430 embedded microcontroller from TI, and as such, some knowledge of the MSP430 architecture is recommended. The MSP430 is used as an example platform only. **Motion Driver can be ported easily to any MCU.**

3. Requirements

3.1 Code Composer Studio (to compile the MSP430 example only)

3.2 Motion Driver source files

3.3 MotionFit™ development board or similar hardware (for example only)

4. Introduction to Motion Driver

Motion Driver consists of a set of API's written in ANSI compatible C to use and configure the different functions of InvenSense Motion Tracking devices, including DMP operation. This tutorial provides a sample project which sends out fused quaternion data from the accelerometer and gyroscope (6-axis Quaternion) onto the serial port of the PC which is processed by a client written in python to display and rotate a 3 dimensional cube on the screen. The 6 axis and 9 axis InvenSense devices are supported in this driver.

The following is addressed in this Motion Driver tutorial:

- How to load, configure, and leverage DMP functions.
- I2C driver example for the MSP430.
- Gyroscope and accelerometer self-test function calls based on the hardware self-test document. (Please refer to the product Register Map document for full self-test descriptions).
- Accelerometer calibration and updating parameters within the hardware registers.
- Gyroscope calibration
- Configuring the low power accelerometer motion interrupt
- Ability to change the sensor Output Data Rate (ODR) of the gyroscope and accelerometer.
- Ability to select which data is populated in the FIFO.

5. Opening up the Motion Driver Project in Code Composer Studio

1. Select import under the file menu.
2. Choose existing CCS eclipse project.
3. Click the browse button to select the Motion Driver folder.

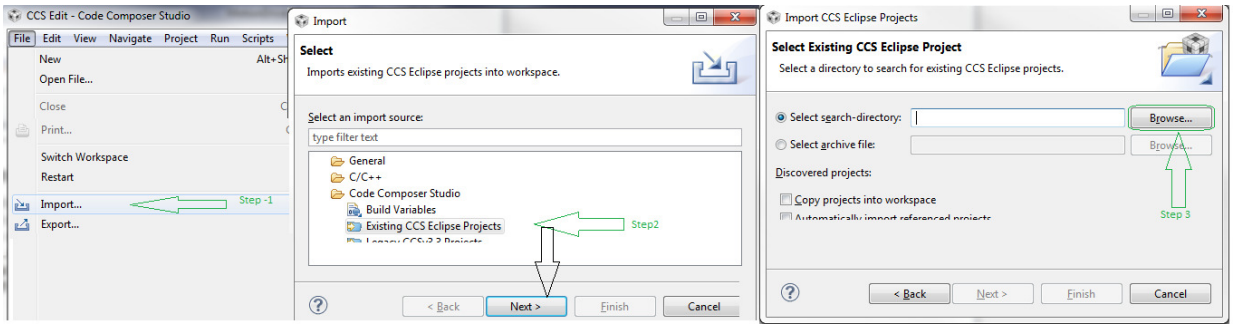


Figure Shows steps 1 to 3 to open the motion driver project

4. Open the Motion Driver project by clicking finish.

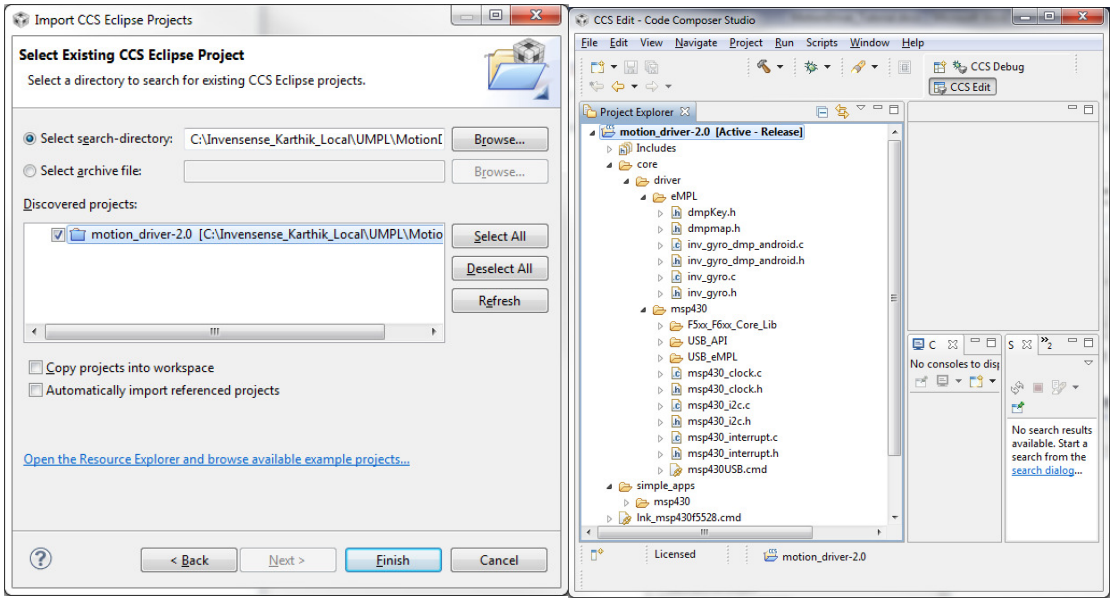


Figure showing the step 4 and the final IDE with Motion Driver

5. Open the file motion_driver_test.c under the simple_apps folder. This file will be referred to as the “main” file throughout this tutorial. The main file includes examples on how to configure the Motion Driver and has in-source documentation to help users read through each line of code.

6. Explaining Motion Driver and the Functional Specification in More Detail

6.1 DMP

1. DMP and DMP features: The DMP is a unique hardware feature of InvenSense MPU devices which is capable of computing quaternion data from sensor readings, performing device calibration, and also includes application specific features such as pedometer step-counting. The DMP image (firmware) is held in volatile memory on the MPU and needs to be updated to the

DMP every time the chip powers up to leverage this functionality. The features which the Motion Driver DMP image supports include:

a) DMP_FEATURE_LP_QUAT: This is a low power (gyro angle) three axis quaternion which is calculated from the gyroscope data at 200HZ within the DMP.
b) DMP_FEATURE_6X_LP_QUAT: This is a low power six axis sensor fusion output calculated from the gyroscope and accelerometer data at 200 Hz within the DMP.
c) DMP_FEATURE_TAP: This is a "tap" gesture feature where one can detect a tap event and sense basic features such as single tap/double tap, or the direction of the tap.
d) DMP_FEATURE_ANDROID_ORIENT: This feature is the implementation of the display orientation as compatible with Google Motion_driver devices. This feature includes a state machine which calculates display orientation.
e) DMP_PEDOMETER: This is a step-counting feature that is always ON and running on the DMP while the MPU is powered. The Motion Driver library can reset pedometer step count value, query for the walk time, and return step count. There is a latency of 7 steps before updating the step count number and walk time to improve accuracy and minimize false-detection. This feature is always enabled as long as the DMP is enabled.
f) DMP_FEATURE_GYRO_CAL: This feature when enabled will calibrate the gyroscope bias whenever the device is in the state of no-motion for more than 8 seconds.
g) DMP_FEATURE_SEND_RAW_ACCEL: Adds raw accelerometer data to the FIFO and the accelerometer data is in chip coordinates
h) DMP_FEATURE_SEND_RAW_GYRO: Add raw gyro data to the FIFO. The gyroscope coordinate is in the chip coordinates.
i) DMP_FEATURE_SEND_CAL_GYRO: Add calibrated gyro data to the FIFO. Cannot be used in combination with DMP_FEATURE_SEND_RAW_GYRO. The output is in the device frame or the body frame instead of chip frame.

2. Steps to load and enable DMP features: The sequence of updating the image and initializing the DMP features is highlighted in the sample application provided within the Motion Driver library project. These steps include:
   a) Push the DMP image into the MPU memory: Helper function dmp_load_motion_driver_firmware is provided for this task.
   b) Push the Gyroscope and Accelerometer Orientation Matrix to the DMP: An orientation matrix can be sent to the DMP to transform the output orientation reference to the board or device coordinate system. dmp_set_orientation () function updates the orientation matrix.
   c) DMP Callbacks: Some DMP features register a call back to alert the main program. These call backs get triggered when the features on the DMP, like orientation ready or tap are detected. There are helper functions provided as an example in the Motion Driver like dmp_register_android_orient_cb(android_orient_cb); for the orientation change feature. Note that registering a call back does not enable a feature by default.
   d) Enable DMP features: Helper function dmp_enable_feature () is provided.
   e) Data Rate: The FIFO rate defines the output data rate of the DMP and can be updated with the helper function mpu_set_fifo_rate (input).

6.2 I2C driver to interface with InvenSense IC

1. An I2C driver is implemented here for the MSP430F5528 platform and is given in source so that it can be easily ported to any MCU platform. msp430_i2c_write and msp430_i2c_read functions provide the primary functionality for reading and writing data while msp430_i2c_enable and msp430_i2c_disable are the functions provided to enable and disable the I2C communication for the MSP430F5528. These functions require the slave address, register address, length and data to be read and written. Please check the file mps430_i2c.c for more details on the implementation.

6.3 Gyroscope and accelerometer self-test function calls

The MPU's gyroscope and accelerometer self-test feature permits users to test the mechanical and electrical portions of the gyroscope and accelerometer. When the self-test is activated, the on-board electronics will actuate the appropriate sensor. This actuation will move the gyroscope's proof masses over a distance equivalent to a pre-defined Coriolis force, simulating an external force on the accelerometer. This results in a change in the sensor output, which is reflected in the output signal. The output signal is used to observe the self-test response in combination with the self-test registers. The self-test response (STR) is defined as follows:

$$\textit{SelfTest Response} = \text{Sensor } \textit{Output with SelfTest Enabled} - \text{Sensor } \textit{Output with SelfTest Disabled}$$

This self-test response is used to determine whether the part has passed or failed the self-test by finding the change from the factory trim of the self-test response:

$$\textit{Change from Factory Trim of the Self- Test Response}(\%) = (STR - FT) / FT$$

The int mpu_run_self_test(long* gyro, long* accel) API is provided by Motion Driver to perform a self-test for the gyroscope and accelerometer. 0 will be returned if the self-test is executed successfully. Gyroscope values obtained from mpu_run_self_test should be scaled to the current gyroscope sensitivity settings. Gyroscope sensitivity parameters can be obtained by calling mpu_get_gyro_sens(float* sens). Scale back the Q16 formatted values of the gyroscope and accelerometer to store the newly obtained gyro bias values.

The accelerometer self-test is performed to ensure that the accelerometer is functioning correctly and is done with the function mpu_run_self_test() which in turn calls another function accel_self_test(accel, accel_st). The **accel_st** parameter refers to the standard accelerometer bias values which can be obtained from the MPU registers by calling get_st_biases.

Refer to the function run_self_test as an example in motion_driver_test.c for more details. Also refer to the following functions for more information:

- mpu_run_self_test
- get_st_biases
- accel_self_test

6.4 Accelerometer calibration

Accelerometer calibration updates bias values if necessary and can be done by comparing the current acceleration values during periods of zero motion by laying down the board on a flat surface. Accelerometer calibration is executed with the function accel_self_test(accel, accel_st), which is included in **inv_mpu.c**. This function retrieves the standard biases of the accelerometer from the MPU registers (function call get_st_biases returns the standard biases) and the current accelerometer reading and then calculates the shift variance of the two to compare it with the maximum and minimum g-values assigned to an instance of **test_s** struct i.e. in **inv_mpu.c**

```
const struct test_s test = {
    .gyro_sens      = 32768/250,
    .accel_sens     = 32768/16,
    .reg_rate_div   = 0,    /* 1kHz. */
    .reg_lpf        = 1,    /* 188Hz. */
    .reg_mpu_fsr    = 0,    /* 250dps. */
    .reg_accel_fsr  = 0x18, /* 16g. */
    .wait_ms        = 50,
    .packet_thresh  = 5,    /* 5% */
    .min_dps        = 10.f,
    .max_dps        = 105.f,
    .max_gyro_var   = 0.14f,
    .min_g          = 0.3f,
    .max_g          = 0.95f,
    .max_accel_var  = 0.14f};
```

To update the accelerometer bias values stored in the MPU hardware registers, call mpu_set_accel_bias. Note that the gyro biases are updated in the DMP memory, while the accelerometer biases are stored in hardware registers. Please refer to the implementation mpu_set_accel_bias for more details.

6.5 Gyroscope calibration

The DMP provides a way to calibrate the gyroscope bias based on a no motion state of the device. This feature can be enabled by selecting the DMP_FEATURE_GYRO_CAL in DMP features. Once this feature is enabled, and if the board is not moving for more than 8 seconds the gyroscope will automatically be calibrated.

6.6 Low power accelerometer motion interrupt

This paragraph explains the section of the driver which helps implement the Low Power (LP) Accelerometer interrupt mode, which can be used to sleep the host processor during periods of no motion, until a motion is detected. The function int mpu_lp_motion_interrupt (unsigned short thresh, unsigned char time, unsigned char lpa_freq) configures the LP Accelerometer interrupt mode with three parameters (further described in the Embedded Motion Driver API Specification document), including threshold, time, and LPA frequency.

In this mode, the device will continue to sample the accelerometer at a fixed frequency, until a signal above the threshold is measured for a period of time. If a time period is chosen which is shorter than the sample period value defined by lpa_freq, the LP Accelerometer interrupt will trigger on the first sample which is of greater value than the defined threshold. Check the individual product specification for more details on the low power accel interrupt.

6.7 Ability to change sensor ODRs of the gyroscope and accelerometer

InvenSense MPUs provide a programmable range of output data rates for the gyroscope and accelerometer. It can be configured by writing a value to the SMPLRT_DIV, gyroscope output data rate can be given as:

Sample Rate = Gyroscope Output Rate / (1 + SMPLRT_DIV)

Motion Driver provides an easy way to configure the ODR of the gyroscope with the function mpu_set_sample_rate**.** However, when the DMP is turned **on**, the gyroscope is preset to a 200Hz sampling rate and mpu_set_sample_rate should not be used. When the DMP is turned **off** the maximum value can be configured up to 8khz, depending on the MPU device specification. When the DLPF is disabled (DLPF_CFG = 0 or 7) then the maximum gyroscope output rate is 8kHz and when the DLPF is enabled it is 1kHz. The maximum accelerometer output rate is 1kHz. For a sample rate greater than 1kHz, the same accelerometer sample may be output to the FIFO, DMP, and sensor registers more than once.

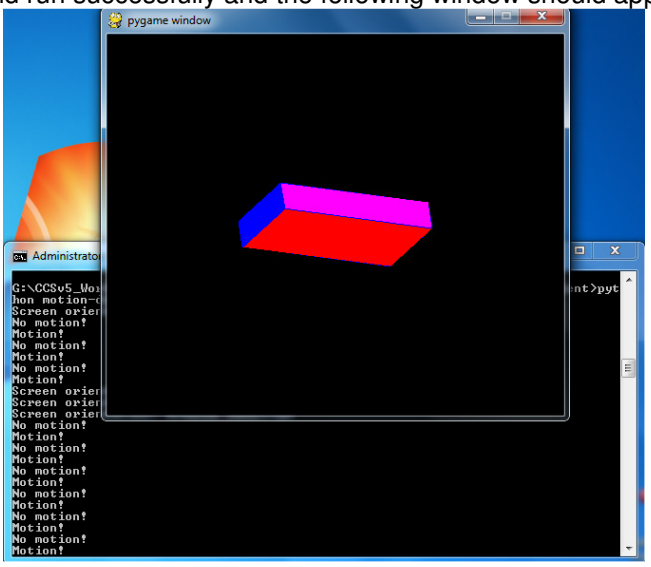
6.8 Ability to select which data to populate in the FIFO using a function call

A FIFO buffer is provided inside the MPU to queue sensor register's values and reduce the required read rate from the MCU. Only accelerometer and gyroscope sensor data can be pushed into the FIFO buffer. Each axis of gyroscope data can be stored in the FIFO independently if desired. Accelerometer output can only be used to save all three axis values simultaneously. Motion Driver provides the function int mpu_configure_fifo(unsigned char sensors) to configure the FIFO buffer. The value of sensors includes a combination of the following flags: INV_X_GYRO, INV_Y_GYRO, INV_Z_GYRO, INV_XYZ_GYRO, INV_XYZ_ACCEL.

7. Testing the Motion Driver Using the MotionFit SDK and Python script

- Build the project and load it on the SDK.

- Connect the USB and point to the .inf file (core\driver\msp430\USB_eMPL*.inf) to install the USB CDC drivers for the SDK.
- Please refer to **APPENDIX A** for installing python if it is not already present on your PC.
- Get the COM port number to which the SDK is connected. Please refer to **APPENDIX B** if you need help finding the COM port number.
- Open the command prompt and change the directory where **motion-driver-client.py** is located e.g. C:\MotionDriver\embedded_motiondriver-Rel-TI_MSP430F5528-MPU6050-V5_1_1-2012-12-14\simple_apps\msp430\motion-driver-client. Now run the **motion–driver-client.py** by typing the following text on the command prompt followed by the port number.
  python motion-driver-client.py 32
  Where 32 is the COM port number that we obtained in Step#4, change it to whatever COM port number you received in Step#4. (See Appendix B)
- The application should run successfully and the following window should appear.



- Motion Driver is provided with a set of commands that can be sent from the PC to perform the various tasks like self-test, etc. Below is the list of commands, prefix the keyword **"inv"** with each command while sending it to the PC, for example command **"a"** should be sent by typing text **"inva"** while the focused windows should be rotating the cube.
  - **a:** Toggle the status of printing accelerometer values over the console.
  - **g:** Toggle the status of printing gyroscope values over the console.
  - **q:** Toggle the status of printing quaternion values over the console.
  - **t:** Run the self-test.
  - **f:** Toggle the DMP.
  - **p:** Read current pedometer count.
  - **x:** Reset the system.
  - **v:** Toggle LP quaternion.
  - **m:** test the motion interrupt
  - **1:** If the DMP is on then it will set the DMP FIFO rate to 10 Hz. If the DMP is off it will set the gyro sample rate to 10Hz
  - **2:** If DMP is on then DMP FIFO rate will be 20Hz, if DMP is off then the gyro sample rate will be 20Hz
  - **3:** 40Hz respectively
  - **4:** 50Hz respectively

- **5:** 100Hz respectively
- **6:** 200Hz respectively
- **7:** Reset pedometer count and walk time to zero.
- **8:** Toggle accelerometer sensor only when the DMP is not ON.
- **9:** Toggle gyroscope sensor only when the DMP is not ON.
- **,:** Set hardware to interrupt on gesture event only. This feature is useful for keeping the MCU asleep until the DMP detects a tap or orientation event.
- **.:** Set hardware to interrupt periodically.

8. Get Compass Data via Motion Driver

If using the InvenSense MPU-9150 with its integrated compass or a 6-axis MPU with an auxiliary compass connected to the secondary I2C bus, motion driver has the capability to pull raw data from the compass. Motion driver function mpu_set_sensors() is used to configure the compass as well by using the INV_XYZ_COMPASS sensor mask. Once it is configured, the function mpu_set_compass_sample_rate() sets the compass sampling rate with a maximum of 100 Hz. mpu_get_compass_reg() function would allow to get the compass data in chip frame.

9. Compass Integration and Calibration

This section provides general guidelines and references on how to integrate and calibrate a compass to achieve 9-axis sensor fusion. **The Motion Driver source does not cover or support any of the compass calibration or 9 axis sensor fusion references pointed out in this section**. This section talks about the compass calibration and integration in general and points to the references from TI and MEMSense which provide application notes and source.

Magnetometer measurements are affected by the presence of the earth's magnetic field and local ferromagnetic materials. Considering an ideal case, magnetic field components along a 3-axis magnetometer should form a sphere whose origin should be at (0, 0, 0). But, this is not the case due to the presence of external effects. If those external effects are from fixed magnetic fields, or "hard iron," then it will cause an offset to the origin of the sphere by (Δx, Δy, Δz), and can be easily calibrated from the earth field data similar to a bias offset calibration. "Soft Iron" effects are the result of materials which bend and distort the local magnetic field, this results in an angle accuracy error. Soft Iron effects should also be removed to get the correct compass values.

The following link below explains and gives the source code to do compass calibration and compass integration. The application notes explain in more detail how the hardware is used.

- http://www.memsense.com/docs/MTD-0802_1.2_Magnetometer_Calibration.pdf
- http://www.ti.com/general/docs/lit/getliterature.tsp?literatureNumber=slaa518a&fileType=pdf

10. SPI driver implementation

InvenSense MPUs communicate to an MCU platform through I2C and/or SPI interface depending on the product specification. The reference MCU for this tutorial, the MSP430F5528, contains a USCI system that provides in total four modules to use with SPI. By default, the MotionFit board does not have SPI lines linked to MSP430 so a separate project is used to test the SPI interface, where a development board is required by the user to test the SPI driver if needed.

The development board utilizes UCSI B1 module for the SPI interface, so currently the SPI driver is configured to be used with that UCSI B1 module. **SPI driver implementation is not a part of the final release for Motion Driver but it is provided as a separate module to illustrate the SPI communication interface between the MPU and the MSP430**. Refer to msp430_spi.c and msp430_spi.h for more details.

In summary, there are four main functions that are given in the SPI driver implementation i.e.

- int msp430_spi_enable(void) : This function is provided to enable the SPI communication interface between the MSP430 and the MPU.
- int msp430_spi_write(unsigned char sel, unsigned char reg_addr, unsigned char length, unsigned char const *data) : This function performs the write operation on the MPU registers provided that SPI is enabled.
- int msp430_spi_read(unsigned char sel, unsigned char reg_addr, unsigned char length, unsigned char *data) : This function performs the read operation on the MPU registers provided that SPI is enabled.
- int msp430_spi_disable() : This function will disable the SPI communication interface between the MPU and the MSP430.
- Note: “sel” parameter which is provided in msp430_spi_read and msp430_spi_write is unnecessary and is included only to replicate the prototypes for I2C read and write functions so that they can be used interchangeably. “Sel” could be used for a chip select pointer if more than one SPI device is connected.
- For more details please refer to the msp430_spi.c and msp430_spi.h and the included SPI testing project which is not a part of Motion Driver but listed separately in a project spi_example_invensense.zip

11. APPENDIX

11.1 APPENDIX A

Motion Driver client console application is provided as a client to Motion Driver. This application is provided as Python source code. It has the following functionality:

1. Provides a simple cube demo for visualizing sensor fusion output.

2. Since the motion driver client is provided as Python source code, the user will need to install the following components to have a working Python environment:

1. Python 2.5.4: The motion driver client was tested with Python 2.5.4 on Windows XP and Windows 7. Download the Windows Installer (python-2.5.4.msi) from http://www.python.org/download/releases/2.5.4/

2. Pyserial 2.5: The motion driver client requires pyserial to communicate on the serial port. Download the Python 2.x Windows Installer (pyserial-2.5.win32.exe) from http://pypi.python.org/pypi/pyserial

3. Pygame 1.9.1: The motion driver client uses the pygame library to render the cube demo. Download the Windows / Python 2.5 release (pygame-1.9.1release.win32-py2.5.exe) from http://www.pygame.org/download.shtml

You must install Python before installing the pyserial and pygame libraries. After installing python use the command prompt to install pyserial. Enter “python install pyserial.py” into the command prompt.

You may want to add Python to your PATH for convenience. In Windows, right click on My Computer, select Properties, and then in the advanced tab select Environment Variables. In the user variables (top section), select Path, click Edit, and add the directory C:\Python25 to the end of the list.

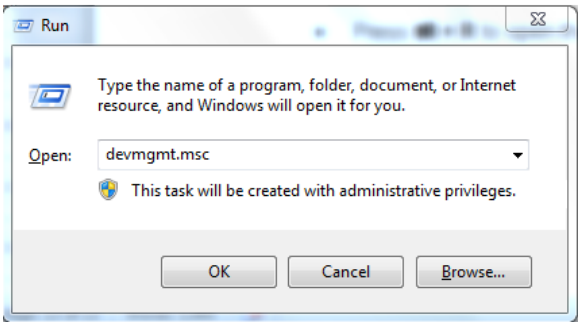
Once you have a working Python environment, you can run the motion driver client application from the command line with the command. To accept data one has to give the python location where python cube is located.

motion-driver-client.py <comport>

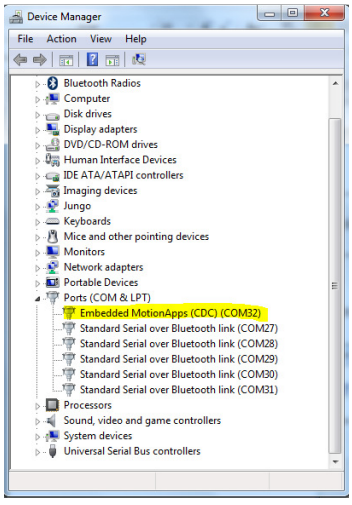
Where <comport> is the COM# detected when the USB driver was installed

11.2 APPENDIX B

Press ⊞ + R to open the Run dialog. Type devmgmt.msc and hit Enter to open the device manager.



Device manager dialog will be opened. Expand the Ports section by clicking on the arrow and look for Embedded Motion Apps (CDC), a COM number should be there next to the port title. This is the port number that should be used with Motion Driver Client i.e.



12. References

[1] Embedded Motion Driver V5.1.1 APIs Specification, Doc# SW-EMD-REL-5.1.1