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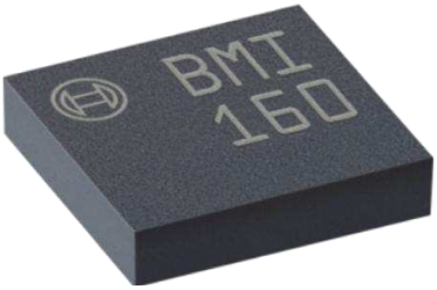
Data sheet

BMI160
Small, low power inertial measurement unit

Bosch Sensortec

BOSCH
Invented for life



BMI160 – Data sheet

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BMI160
Small, low Power Inertial Measurement Unit

The BMI160 is a highly integrated, low power inertial measurement unit (IMU) that provides precise acceleration and angular rate (gyroscopic) measurement.

The BMI160 integrates:
- 16 bit digital, triaxial accelerometer
- 16 bit digital, triaxial gyroscope

Key features
- High performance accelerometer and gyroscope (hardware synchronized)
- Very low power consumption: typ. 925 µA (accelerometer and gyroscope in full operation)
- Android Lollipop compatible: significant motion and step detector / step counter (5 µA each)
- Very small 2.5 x 3.0 mm^2 footprint, height 0.83 mm
- Built-in power management unit (PMU) for advanced power management
- Power saving with fast start-up mode of gyroscope
- Wide power supply range: 1.71V ... 3.6V
- Allocatable FIFO buffer of 1024 bytes (capable of handling external sensor data)
- Hardware sensor time-stamps for accurate sensor data fusion
- Integrated interrupts for enhanced autonomous motion detection
- Flexible digital primary interface to connect to host over I^{2}C or SPI
- Extended I^{2}C mode with clock frequencies up to 1 MHz
- Additional secondary high speed interface for OIS application
- Capable of handling external sensor data
  (e.g. geomagnetic or barometric pressure sensors by Bosch Sensortec)

Typical applications
- Augmented Reality
- Indoor navigation
- 3D scanning / indoor mapping
- Advanced gesture recognition
- Immersive gaming
- 9-axis motion detection
- Air mouse applications and pointers
- Pedometer / step counting
- Advanced system power management for mobile applications
- Optical image stabilization of camera modules
- Free-fall detection and warranty logging

Target Devices
- Smart phones, tablet and transformer PCs
- Game controllers, remote controls and pointing devices
- Head tracking devices
- Wearable devices, e.g. smart watches or augmented reality glasses
- Sport and fitness devices
- Cameras, camera modules
- Toys, e.g. toy helicopters

General Description

The BMI160 is an inertial measurement unit (IMU) consisting of a state-of-the-art 3-axis, low-g accelerometer and a low power 3-axis gyroscope. It has been designed for low power, high precision 6-axis and 9-axis applications in mobile phones, tablets, wearable devices, remote controls, game controllers, head-mounted devices and toys. The BMI160 is available in a compact 14-pin 2.5 × 3.0 × 0.83 mm^3 LGA package. When accelerometer and gyroscope are in full operation mode, power consumption is typically 925 µA, enabling always-on applications in battery driven devices. The BMI160 offers a wide V_{DD} voltage range from 1.71V to 3.6V and a V_{DDIO} range from 1.2V to 3.6V, allowing the BMI160 to be powered at 1.8V for both V_{DD} and V_{DDIO}.

Due to its built-in hardware synchronization of the inertial sensor data and its ability to synchronize data of external devices such as geomagnetic sensors, BMI160 is ideally suited for augmented reality, gaming and navigation applications, which require highly accurate sensor data fusion. The BMI160 provides high precision sensor data together with the accurate timing of the corresponding data. The timestamps have a resolution of only 39 µs.

Further Bosch Sensortec sensors, e.g. geomagnetic (BMM150) can be connected as slave via a secondary I^2C interface. In this configuration, the BMI160 controls the data acquisition of the external sensor and the synchronized data of all sensors is stored the register data and can be additionally stored in the built-in FIFO.

The integrated 1024 byte FIFO buffer supports low power applications and prevents data loss in non-real-time systems. The intelligent FIFO architecture allows dynamic reallocation of FIFO space for accelerometer, gyroscope and external sensors, respectively. For typical 6-DoF applications, this is sufficient for approx. 0.75 s of data capture. In a typical 9-DoF application – including the geomagnetic sensor – this is sufficient for approx. 0.5 s.

Like its predecessors, the BMI160 features an on-chip interrupt engine enabling low-power motion-based gesture recognition and context awareness. Examples of interrupts that can be issued in a power efficient manner are: any- or no-motion detection, tap or double tap sensing, orientation detection, free-fall or shock events. The BMI160 is Android 5.0 (Lollipop) compatible, and in the implementation of the Significant Motion and Step Detector interrupts, each consumes less than 20µA.

The smart built-in power management unit (PMU) can be configured, for example, to further lower the power consumption by automatically sending the gyroscope temporarily into fast start-up mode and waking it up again by internally using the any-motion interrupt of the accelerometer. By allowing longer sleep times of the host, the PMU contributes to significant further power saving on system level.

Besides the flexible primary interface (I^2C or SPI) that is used to connect to the host, BMI160 provides an additional secondary interface. This secondary interface can be used in SPI mode for OIS (optical image stabilization) applications in conjunction with camera modules, or in advanced gaming use cases. When connected to a geomagnetic sensor, BMI160 will trigger autonomous read-out of the sensor data from magnetometer without the need for intervention by the host processor.

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1. Specification

If not stated otherwise, the given values are over lifetime and full performance temperature and voltage ranges, minimum/maximum values are ±3σ. The specifications are split into accelerometer and gyroscope sections of the BMI160.

1.1 Electrical specification

VDD and VDDIO can be ramped in arbitrary order without causing the device to consume significant currents. The values of the voltage at VDD and the VDDIO pins can be chosen arbitrarily within their respective limits. The device only operates within specifications if the both voltages at VDD and VDDIO pins are within the specified range. The voltage levels at the digital input pins must not fall below GNDIO-0.3V or go above VDDIO+0.3V to prevent excessive current flowing into the respective input pin. BMI160 contains a brownout detector, which ensures integrity of data in the non-volatile memory under all operating conditions.

Table 1: Electrical parameter specification

OPERATING CONDITIONS BMI160						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Unit**
Supply Voltage Internal Domains	V_{DD}		1.71	3.0	3.6	V
Supply Voltage I/O Domain	V_{DDIO}		1.2	2.4	3.6	V
Voltage Input Low Level	$V_{IL,a}$	SPI			$0.3V_{DDIO}$	-
Voltage Input High Level	$V_{IH,a}$	SPI	$0.7V_{DDIO}$			-
Voltage Output Low Level	$V_{OL,a}$	V_{DDIO}=1.62V, I_{OL}=3mA, SPI			$0.2V_{DDIO}$	-
		V_{DDIO}=1.2V, I_{OL}=3mA, SPI			$0.23V_{DDIO}$	-
Voltage Output High Level	$V_{OH,a}$	V_{DDIO}=1.62V, I_{OH}=3mA, SPI	$0.8V_{DDIO}$			-
		V_{DDIO}=1.2V, I_{OH}=3mA, SPI	$0.62V_{DDIO}$			-
Operating Temperature	T_A		-40		+85	°C
NVM write-cycles	n_{NVM}	Non-volatile memory	14			Cycles
Current consumption	I_{DD}	Gyro in fast start-up, accel in suspend mode, T_A=25°C		500	600	µA
		Gyro and accel full operation mode, T_A=25°C		925	990	
		Gyro full operation mode, accel in suspend, T_A=25°C		850	900	
		Accel full operation mode, gyro in suspend, T_A=25°C		180	300	
		Gyro and accel in suspend mode, T_A=25°C		3	10	
		Significant motion detector, gyro in suspend, accel in low power mode @50Hz, T_A=25°C			20	
		Step detector, gyro in suspend, accel in low power mode @50Hz, T_A=25°C			20	

1.2 Electrical and physical characteristics, measurement performance

Table 2: Electrical characteristics accelerometer

Operating Conditions Accelerometer						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Units**
Acceleration Range	g_{FS2g}	Selectable via serial digital interface		±2		g
	g_{FS4g}			±4		g
	g_{FS8g}			±8		g
	g_{FS16g}			±16		g
Start-up time	$t_{A,su}$	Suspend/low power mode to normal mode, ODR=1.6kHz		3.2	3.8	ms

Output Signal Accelerometer						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Units**
Resolution				16		bit
Sensitivity	S_{2g}	g_{FS2g}, T_A=25°C	15729	16384	17039	LSB/g
	S_{4g}	g_{FS4g}, T_A=25°C	7864	8192	8520	LSB/g
	S_{8g}	g_{FS8g}, T_A=25°C	3932	4096	4260	LSB/g
	S_{16g}	g_{FS16g}, T_A=25°C	1966	2048	2130	LSB/g
Sensitivity Temperature Drift	TCS_A	g_{FS8g}, Nominal V_{DD} supplies best fit straight line		±0.03		%/K
Sensitivity change over supply voltage	$S_{A,VDD}$	T_A=25°C, $V_{DD,min} \leq V_{DD} \leq V_{DD,max}$ best fit straight line		0.01		%/V
Zero-g Offset	$Off_{A,\ init}$	g_{FS8g}, T_A=25°C, nominal V_{DD} supplies, component level		±25		mg
	$Off_{A,board}$	g_{FS8g}, T_A=25°C, nominal V_{DD} supplies, soldered, board level		±40		mg
	$Off_{A,MSL}$	g_{FS8g}, T_A=25°C, nominal V_{DD} supplies, after MSL1-prec. [1] / soldered		±70		mg
	$Off_{A,life}$	g_{FS8g}, T_A=25°C, nominal V_{DD} supplies, soldered, over life time[2]		±150		mg
Zero-g Offset Temperature Drift	TCO_A	g_{FS8g}, Nominal V_{DD} supplies best fit straight line		±1.0		mg/K
Nonlinearity	NL_A	Best fit straight line, g_{FS8g}		±0.5		%FS
Output Noise	$n_{A,nd}$	g_{FS8g}, T_A=25°C, nominal V_{DD}, Normal mode		180	300	µg/√Hz

[1] Values taken from qualification, according to JEDEC J-STD-020D.1
[2] Values taken from qualification, according to JEDEC J-STD-020D.1

	$n_{A,rms}$	Filter setting 80 Hz, ODR 200 Hz		1.8		mg-rms
Cross Axis Sensitivity	S_A	Relative contribution between any two of the three axes		1		%
Alignment Error	E_A	Relative to package outline		±0.5		°
Output Data rate (set of x,y,z rate)	ODR_A		12.5		1600	Hz
Output Data rate accuracy (set of x,y,z rate)	$AODR_A$	Normal mode, over whole operating temperature range		±1		%

Table 3: Electrical characteristics gyroscope

Operating Conditions Gyroscope						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Unit**
Range	R_{FS125}	Selectable via serial digital interface		125		°/s
	R_{FS250}			250		°/s
	R_{FS500}			500		°/s
	R_{FS1000}			1,000		°/s
	R_{FS2000}			2,000		°/s
Start-up time	$t_{G,su}$	Suspend to normal mode ODR_G=1600Hz		55		ms
	$t_{G,FS}$	Fast start-up to normal mode		10		ms

Output Signal Gyroscope						
Sensitivity	R_{FS2000}	Ta=25°C	15.9	16.4	16.9	LSB/°/s
	R_{FS1000}	Ta=25°C	31.8	32.8	33.8	LSB/°/s
	R_{FS500}	Ta=25°C	63.6	65.6	67.6	LSB/°/s
	R_{FS250}	Ta=25°C	127.2	131.2	135.2	LSB/°/s
	R_{FS125}	Ta=25°C	254.5	262.4	270.3	LSB/°/s
Sensitivity change over temperature	TCS_G	R_{FS2000}, Nominal V_{DD} supplies best fit straight line		±0.02		%/K
Sensitivity change over supply voltage	$S_{G,VDD}$	T_A=25°C, $V_{DD,min} \leqslant V_{DD} \leqslant V_{DD,max}$ best fit straight line		0.01		%/V
Nonlinearity	NL_G	Best fit straight line R_{FS1000}, R_{FS2000}		0.1		%FS
g- Sensitivity		Sensitivity to acceleration stimuli in all three axis (frequency <20kHz)			0.1	°/s/g
Zero-rate offset	Off Ω_x Ω_y and Ω_z	T_A=25°C, fast offset compensation off		±3		°/s

Zero-Rate offset Over temperature	Off $\Omega_{x,oT}$ $\Omega_{y,oT}$ and $\Omega_{z,oT}$	-40°C ≤ T_A ≤+85°C		±3		°/s
Zero-rate offset change over temperature	TCO_G	-40°C ≤ T_A ≤+85°C, best fit straight line		0.05		°/s/K
Output Noise	$n_{G,nD}$	@10 Hz		0.007		°/s/√Hz
	$n_{G,rms}$	Filter setting 74.6Hz, ODR 200 Hz		0.07		°/s rms
Output Data Rate (set of x,y,z rate)	ODR_G		25		3200	Hz
Output Data rate accuracy (set of x,y,z rate)	$AODR_G$	Over whole operating temperature range		±1		%
Cross Axis Sensitivity	$X_{G,S}$	Sensitivity to stimuli in non-sense-direction			2	%

Table 4: Electrical characteristics temperature sensor

Operating Conditions and Output signal of Temperature Sensor						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Unit**
Temperature Sensor Measurement Range	T_S		-40		85	°C
Temperature Sensor Slope	dT_S			0.002		K/LSB
Temperature Sensor Offset	OT_S			±2	±5	K
Output Data Rate	ODR_T	Accelerometer on or gyro in fast start-up		0.8		Hz
		Gyro active		100		Hz
Resolution	n_T	Accelerometer on or gyro in fast start-up		8		bit
		Gyro active		16		bit

1.3 Absolute maximum ratings

Table 5: Absolute maximum ratings

Parameter	Condition	Min	Max	Units
Voltage at Supply Pin	V_{DD} Pin	-0.3	4.25	V
	V_{DDIO} Pin	-0.3	4.25	V
Voltage at any Logic Pin	Non-Supply Pin	-0.3	V_{DDIO}+0.3	V
Passive Storage Temp. Range	≤65% rel. H.	-50	+150	°C
None-volatile memory (NVM) Data Retention	T = 85°C, after 15 cycles	10		y
Mechanical Shock	Duration 200 µs, half sine		10,000	g
	Duration 1.0 ms, half sine		2,000	g
	Free fall onto hard surfaces		1.8	m
ESD	HBM, at any Pin		2	kV
	CDM		500	V
	MM		200	V

Note: Stresses above these listed maximum ratings may cause permanent damage to the device. Exposure beyond specified electrical characteristics as specified in Table 1 may affect device reliability or cause malfunction.

2. Functional Description

2.1 Block diagram

The figure below depicts the dataflow in BMI160 and the configuration parameters for data rates:

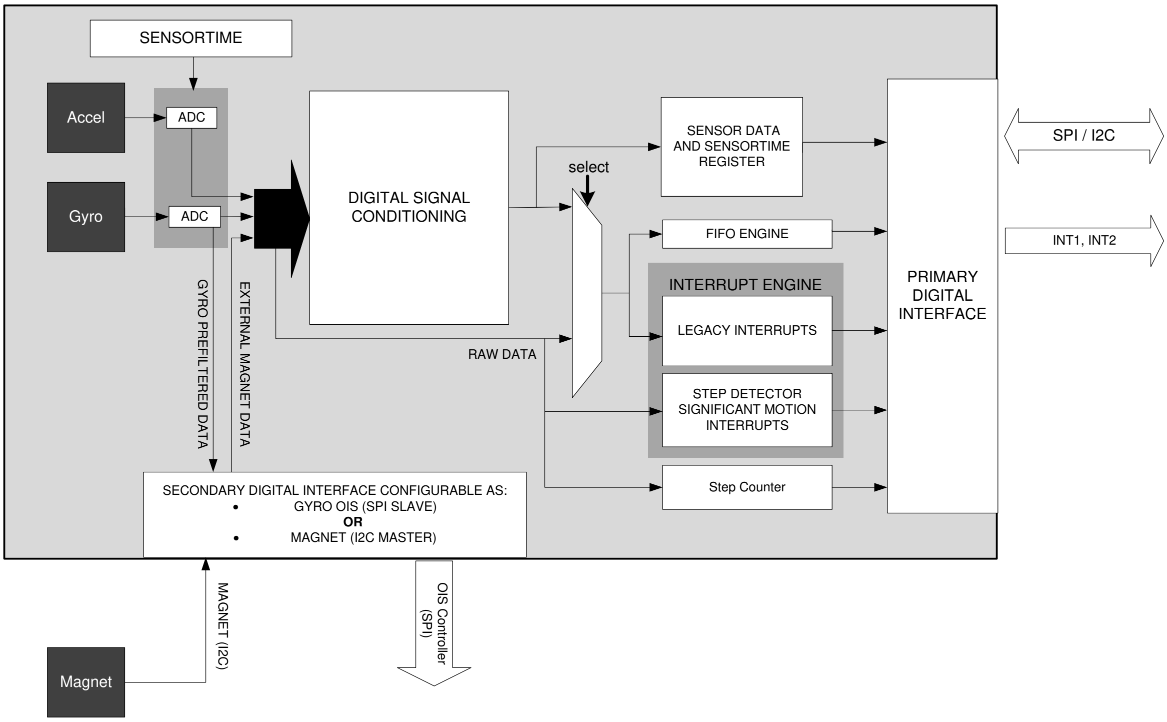

Figure 1: Block diagram of data flow

The pre-filtered input data may be already temperature compensated or other low level correction operations may be applied to them.
The data from the sensor are always sampled with a data rate of 6400 Hz for the gyroscope and 1600 Hz for the accelerometer. The data are filtered to an output data rate configured in the Register (0x40) ACC_CONF and Register (0x42) GYR_CONF for accelerometer and gyroscope, respectively. The data processing implements a low pass filter configured in the Register (0x40) ACC_CONF and Register (0x42) GYR_CONF for accelerometer and gyroscope, respectively. In addition further down sampling for the interrupt engines and the FIFO is possible and configured in the Register (0x45) FIFO_DOWNS. This down sampling discards data frames.
The sensor time is synchronized with the update of the data register. Synchronization is a purely digital statement.

2.2 Power modes

By default BMI160 accel and gyro are in suspend mode after powering up the device. The device is powering up in less than 10ms.

Three power modes are supported for accelerometer and gyroscope:

Accelerometer

- **Normal mode:** full chip operation
- **Low power mode**: duty-cycling between suspend and normal mode. FIFO data readout are supported in lower power mode to a limited extent, see Register PMU_STATUS.
- **Suspend mode**: No sampling takes place, all data is retained, and delays between subsequent I^2C operations are allowed. FIFO data readout is not supported in suspend mode.

Gyroscope

- **Normal mode:** same as accelerometer
- **Suspend mode:** same as accelerometer
- **Fast start-up mode:** start-up delay time to normal mode ≤10 ms

Table 6: Power modes of accelerometer and gyro in BMI160

		Accelerometer	**Gyroscope**	**external Magnetometer BMM150**
full operation mode	Normal mode	✓	✓	✓
Sleep modes	Fast Start-up mode		✓	
	Suspend mode	✓	✓	✓
Low power modes	Low power mode	✓		✓

Suspend and fast start-up modes are *sleep modes*. Switching between normal and low power mode will not impact the output data from the sensor. This allows the system to switch from low power mode to normal mode to read out the sensor data in the FIFO with a data rate limited by the serial interface.

2.2.1 Suspend mode (accelerometer and gyroscope)

In suspend mode, the MEMS sensors are powered off but the digital circuitry is still active.

<u>Note:</u>
When all sensors are in suspend or low power mode, burst writes are not supported, normal writes need wait times after the write command is issued (~400 µs), and burst reads are not supported on Register (0x24) FIFO_DATA. If all sensors (accelerometer, gyroscope or magnetometer) are in either suspend or low power mode, the FIFO must not be read.

2.2.2 Fast start-up mode (gyroscope only)

In **fast start-up mode** the sensing analog part is powered down, while the drive and the digital part remains largely operational. No data acquisition is performed. The latest rate data and the content of all configuration registers are kept. The fast start-up mode allows a fast transition (≤10 ms) into normal mode while keeping power consumption significantly lower than in normal mode.

2.2.3 Transitions between power modes

The table below for the power modes of gyroscope and accelerometer shows which power mode combinations are supported by BMI160.

With regard to the below diagram, transitions between power modes are only allowed in horizontal or vertical direction. Transitions in diagonal direction are not supported.

Table 7: Typical total current consumption in µA according to accel/gyro modes

Current consumption in µA		Accelerometer Mode		
		Suspend	**Normal**	**Low Power**
Gyroscope Mode	**Suspend**	3	180	See Table 8
	Fast Start-up	500	580	n.a.
	Normal	850	925	n.a.

The power mode setting can be configures independently from the output data rate set. The main difference between normal and low power mode is the power consumption as shown in the figure below. If the sleep time between two configured sampling intervals becomes too short to duty cycle between suspend and normal mode, the accelerometer stays automatically in normal mode. In order to make the transition between low power and normal mode as transparent as possible, an undersampling mode is defined in such a way that it mimics the behavior of the lower data rate in low power mode in normal mode. The low power mode then only switches clock sources.

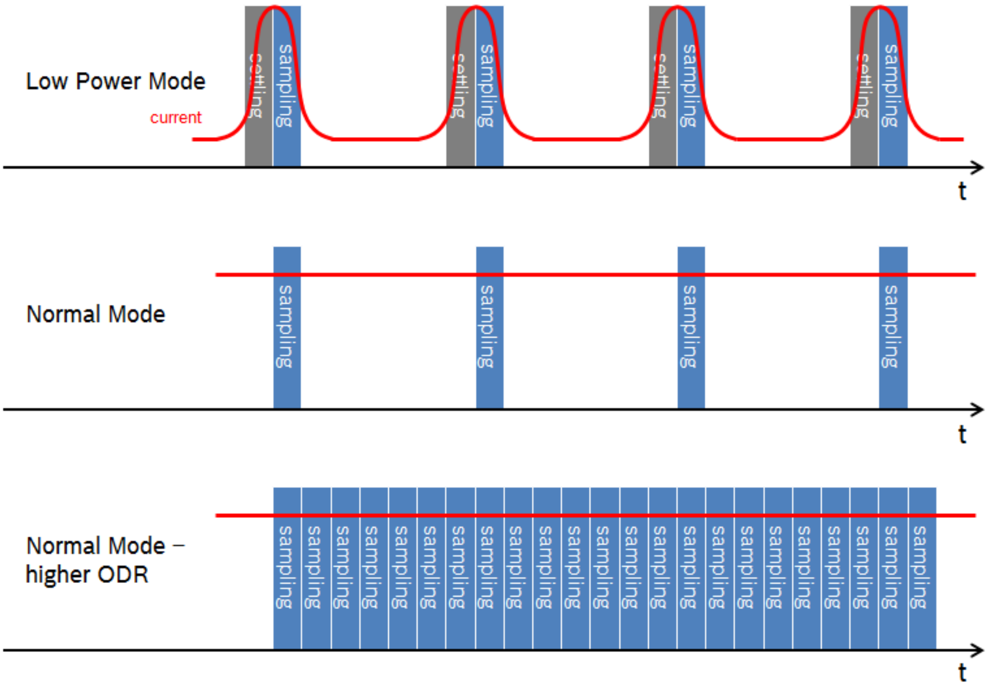

Figure 2: low power and normal mode operation

2.2.4 Low power mode (accelerometer only)

In low power modes the accelerometer toggles between normal mode and suspend mode. The power consumption is given by the power consumption in normal mode times the fraction of time the sensor is in normal mode. The time in normal mode is defined by the startup time of the MEMS element, plus the analogue settling time. This results in a minimum time in normal mode of the settling time plus (averaged samples)/1600 Hz.

Regarding register read and write operations, the note in chapter 2.2.1 applies.

2.2.4.1 Power Consumption in accelerometer low power mode

When accelerometer and gyroscope are operated in normal mode, there is no significant dependence on the specific settings like ODR, undersampling and bandwidth. The same applies to the fast power up mode of the gyroscope. If the accelerometer, however, is operated in low power mode and undersampling is enabled, the power consumption of the accel depends on the two parameters ODR and number of averaging cycles.

In low power mode (gyroscope in suspend), the actual power consumption depends on the selected setting in Register (0x40) ACC_CONF.

Table 8: Typical total current consumption in µA according to number of averaging cycles and accelerometer ODR settings (gyroscope in suspend mode and accelerometer in low power mode and undersampling)

Typical current consumption in µA		**AVG – number of averaging cycles**							
		1	2	4	8	16	32	64	128
ODR of accelerometer in low power mode [Hz] (gyroscope in suspend mode)	0,78125	5	5	5	5	6	7	9	14
	1,5625	5	5	5	7	7	9	14	23
	3,125	5	5	6	7	9	14	23	42
	6,25	6	6	7	9	14	24	42	82
	12,5	6	8	10	14	24	44	84	n. m.
	25	8	11	17	25	47	90	normal mode	
	50	12	18	27	51	100	normal mode		
	100	24	41	53	138	normal mode			
	200	86	118	163	normal mode				
	400	166	166	normal mode					
	800	normal mode							
	1600	normal mode							

2.2.4.2 Noise of accelerometer in low power mode

When acc_us=1, accelerometer is in undersampling mode. The noise is only depending on the number of averaging cycles

Table 9: Accel noise in mg according to averaging with undersampling (range +/- 8g)

AVG – number of averaging cycles	**1**	**2**	**4**	**8**	**16**	**32**	**64**	**128**
RMS-noise (typ.) [mg]	4.3	3.5	3.0	2.0	1.5	1.1	0.7	0.5

2.2.5 PMU (Power Management Unit)

The integrated PMU (Power Management Unit) allows advanced power management features by combining power management features of all built-in sensors and externally available wake-up devices.
See chapter 2.6.11, PMU Trigger (Gyro).

2.2.5.1 Automatic gyroscope power mode changes

To further lower the power consumption, the gyroscope may be configured to be temporarily put into sleep mode, which is in BMI160 configurable as suspend or fast-start-up mode, when no motion is detected by the accelerometer. This mode benefits from the accelerometer any-motion and nomotion interrupt that is used to control the power state of the gyroscope. To configure this feature Register (0x6C) PMU_TRIGGER is used.

2.2.5.2 Power management with external geomagnetic sensor

An external magnetometer can be connected via the secondary interface. The drivers support Bosch Sensortec devices. The PMU allows advanced power management with the external magnetometer.

Table 10: Supported magnetometer and accelerometer power modes (only horizontal and vertical transitions are allowed)

		Accel		
		Suspend	**Normal**	**Low power**
Magnetometer	**Suspend**	Supported	Supported	Supported
	Normal	Supported	Supported	Supported

Note, for setting the magnetometer to suspend mode it is required to put the magnetometer itself into suspend mode through the magnetometer interface manual mode *mag_man_en* in Register (0x4B-0x4F) MAG_IF and to set the magnetometer interface after that to suspend using a *mag_set_pmu_mode* command in the Register (0x7E) CMD. Changing the magnetometer interface power mode to suspend does not imply any mode change in the magnetometer.

2.3 Sensor Timing and Data synchronization

2.3.1 Sensor Time

The Register (0x18-0x1A) SENSORTIME is a free running counter, which increments with a resolution of 39 µs. All sensor events e.g. updates of data registers are synchronous to this register as defined in the table below. With every update of the data register or the FIFO, a bit *m* in the Register (0x18-0x1A) SENSORTIME toggles where *m* depends on the output data rate for the data register and the output data rate and the FIFO down sampling rate for the FIFO. The table below shows which bit toggles for which update rate of data register and FIFO. The time stamps in Register (0x18-0x1A) SENSORTIME are available independent of the power mode the device is in.

Table 11: Sensor time

Bit *m* in sensor_time	Resolution [ms]	Update rate [Hz]
0	0.039	25641
1	0.078	12820
2	0.156	6400
3	0.3125	3200
4	0.625	1600
5	1.25	800
6	2.5	400
7	5	200
8	10	100
9	20	50
10	40	25
11	80	12.5
12	160	6.25
13	320	3.125
14	640	1.56
15	1280	0.78
16	2560	0.39
17	5120	0.20
18	10240	0.10
19	20480	0.049
20	40960	0.024
21	81920	0.012
22	163840	0.0061
23	327680	0.0031

2.3.2 Data synchronization

The sensor data from accelerometer and gyroscope are strictly synchronized on hardware level, i.e. they run on exactly the same sampling rate.

BMI160 supports various level of data synchronization:

- Internal hardware synchronization of accelerometer, gyroscope and external sensor data.
- High precision synchronization of external data with sensor data through hardware timestamps. The hardware timestamp resolution is 39 µs.
- Hardware synchronization of the data of accelerometer, gyro and external sensor through a unique DRDY interrupt signal.
- FIFO entries of the accelerometer, gyro and external sensor are already synchronized by hardware. The according time stamp can be provided with each full FIFO read.
- Synchronization of external data (e.g. magnetometer data) with FIFO data at data sampling granularity through hardware signaling

2.4 Data Processing

The accelerometer digital filter can be configured through the parameters: *acc_bwp*, *acc_odr* and *acc_us*. The gyroscope digital filter can be configured through the parameters: *gyr_bwp* and *gyr_odr*. There is no undersampling parameter for the gyroscope.

Note:
Illegal settings in configuration registers will result in an error code in the Register (0x02) ERR_REG. The content of the data register is undefined, and if the FIFO is used, it may contain no value.

2.4.1 Data Processing Accelerometer

The accelerometer digital filter can be configured through the parameters: *acc_bwp*, *acc_odr* and *acc_us* in Register (0x40) ACC_CONF for the accelerometer. The gyroscope data can only be processed in normal power mode or in low power mode.

2.4.1.1 Accelerometer data processing for normal power mode

When normal power mode is used, the undersampling mode should be disabled (acc_us=0b0). In this configuration mode, the accelerometer data is sampled at equidistant points in the time, defined by the accelerometer output data rate parameter (acc_odr). The output data rate can be configured in one of eight different valid ODR configurations going from 12.5Hz up to 1600Hz.

Note: Lower ODR values than 12.5Hz are not allowed when undersampling mode is not enabled. If they are used they result in an error code in Register (0x02) ERR_REG.

When acc_us=0b0, the acc_bwp parameter needs to be set to 0b010 (normal mode).
The filter bandwidth shows a 3db cutoff frequency shown in the following table:

Table 12: 3dB cutoff frequency of the accelerometer according to ODR with normal filter mode

Accelerometer ODR [Hz]	**12,5**	**25**	**50**	**100**	**200**	**400**	**800**	**1600**
3dB Cutoff frequency [Hz]	5.06	10.12	20.25	40.5	80	162 (155 for Z axis)	324 (262 for Z axis)	684 (353 for Z axis)

The noise is also depending on the filter settings and ODR, see table below.

Table 13: Accelerometer noise in mg according to ODR with normal filter mode (range +/- 8g)

ODR in Hz	**25**	**50**	**100**	**200**	**400**	**800**	**1600**
RMS-Noise (typ.) [mg]	0.6	0.7	1.0	1.5	2.2	2.8	4.3

When the filter mode is set to **OSR2** (acc_bwp=0b001 and acc_us=0b0), both stages of the digital filter are used and the data is oversampled with an oversampling rate of 2. That means that for a certain filter configuration, the ODR has to be 2 times higher than in the normal filter mode. Conversely, for a certain filter configuration, the filter bandwidth will be the half of the bandwidth achieved for the same ODR in the normal filter mode. For example, for ODR=50Hz we will have a 3dB cutoff frequency of 10.12Hz.

When the filter mode is set to **OSR4** (acc_bwp=0b000 and acc_us=0b0), both stages of the digital filter are used and the data is oversampled with an oversampling rate of 4. That means that for a certain filter configuration, the ODR has to be 4 times higher than in the normal filter mode. Conversely, for a certain filter configuration, the filter bandwidth will be 4 times smaller than the bandwidth achieved for the same ODR in the normal filter mode. For example, for ODR=50Hz we will have a 3dB cutoff frequency of 5.06Hz.

2.4.1.2 Accelerometer data processing for low power mode

When low power mode is used, the undersampling mode must be enabled (acc_us=0b1). In this configuration mode, the accelerometer regularly changes between a suspend power mode phase where no measurement is performed and a normal power mode phase, where data is acquired. The period of the duty cycle for changing between suspend and normal mode will be determined by the output data rate (acc_odr). The output data rate can be configured in one of 12 different valid ODR configurations going from 0.78Hz up to 1600Hz.
The samples acquired during the normal mode phase will be averaged and the result will be the output data. The number of averaged samples can be determined by the parameter acc_bwp through the following formula:

$$\text{averaged samples} = 2^{(Val(acc\_bwp))}$$
$$\text{skipped samples} = (1600/ODR)\text{-averaged samples}$$

A higher number of averaged samples will result in a lower noise level of the signal, but since the normal power mode phase is increased, the power consumption will also rise. This relationship can be observed in chapter Power Consumption.

Note: When undersampling (*acc_us*=0b1 in Register (0x40) ACC_CONF) and the use of pre-filtered data for interrupts or FIFO is configured an error code is flagged in Register (0x02) ERR_REG. Pre-filtered data for interrupts are configured through *int_motion_src*=0b1 or *int_tap_src*=0b1 in Register (0x58-0x59) INT_DATA. Pre-filtered data for the FIFO are configured through *acc_fifo_filt_data*=0b0 in Register (0x45) FIFO_DOWNS.

2.4.2 Data Processing Gyroscope

The gyroscope digital filter can be configured through the parameters: *gyr_bwp* and *gyr_odr* in GYR_CONF for the gyroscope. There is no undersampling option for the gyroscope data processing. The gyroscope data can only be processed in normal power mode.
There are three data processing modes defined by gyr_bwp. Normal mode, OSR2, OSR4. For details see chapter 2.11.13.

2.4.2.1 Gyroscope data processing for normal power mode

When the filter mode is set to normal (gyr_bwp=0b010), the gyroscope data is sampled at equidistant points in the time, defined by the gyroscope output data rate parameter (gyr_odr). The output data rate can be configured in one of eight different valid ODR configurations going from 25Hz up to 3200Hz.

Note: Lower ODR values than 25Hz are not allowed. If they are used they result in an error code in Register (0x02) ERR_REG.

The filter bandwidth as configured by gyr-odr shows a 3db cutoff frequency shown in the following table:

Gyroscope ODR [Hz]	25	50	100	200	400	800	1600	3200
3dB Cutoff frequency [Hz]	10.7	20.8	39.9	74.6	136.6	254.6	523.9	890

When the filter mode is set to **OSR2** (gyr_bwp=0b001), both stages of the digital filter are used and the data is oversampled with an oversampling rate of 2. That means that for a certain filter configuration, the ODR has to be 2 times higher than in the normal filter mode. Conversely, for a certain filter configuration, the filter bandwidth will be the approximately half of the bandwidth achieved for the same ODR in the normal filter mode. For example, for ODR=50Hz we will have a 3dB cutoff frequency of 10.12Hz.

When the filter mode is set to **OSR4** (gyr_bwp=0b000), both stages of the digital filter are used and the data is oversampled with an oversampling rate of 4. That means that for a certain filter configuration, the ODR has to be 4 times higher than in the normal filter mode. Conversely, for a certain filter configuration, the filter bandwidth will be approximately 4 times smaller than the bandwidth achieved for the same ODR in the normal filter mode. For example, for ODR=50Hz we will have a 3dB cutoff frequency of 5.06Hz.

Note: the gyroscope doesn't feature a low power mode. Therefore, there is also no undersampling mode for the gyroscope data processing.

2.5 FIFO

A FIFO is integrated in BMI160 to support low power applications and prevent data loss in non-real-time systems. The FIFO has a size of 1024 bytes. The FIFO architecture supports to dynamically allocate FIFO space for accelerometer and gyroscope. For typical 6 DoF applications, this is sufficient for approx. 0.75 s of data capture. In typical 9DoF applications – including the magnetometer – this is sufficient for approx. 0.5 s. If not all sensors are enabled or lower ODR is used on one or more sensors, FIFO size will be sufficient for capturing data longer, increasing ODR of one or more sensors will reduce available capturing time. The FIFO features a FIFO full and watermark interrupt. Details can be found in chapter 2.6.12.

A schematic of the data path when the FIFO is used is shown in the figure below.

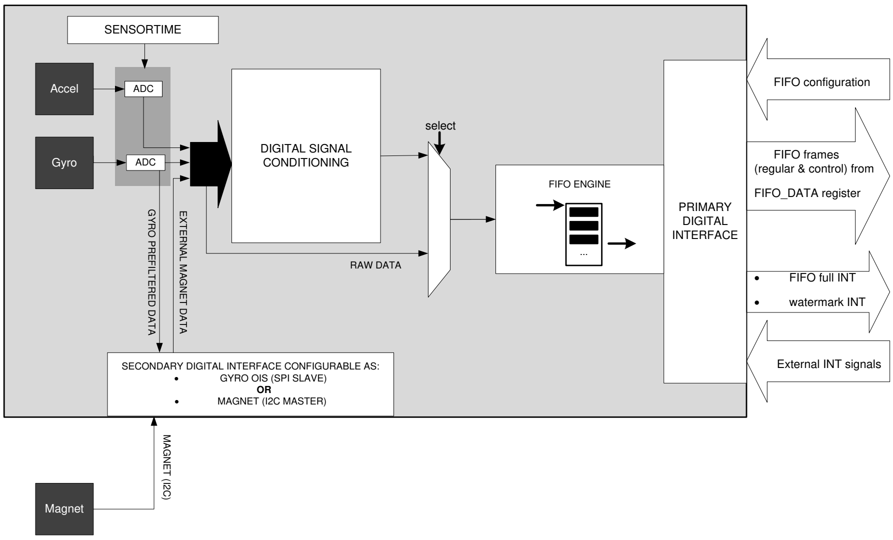

Figure 3: Block diagram of FIFO data path

2.5.1 FIFO Frames

When using the FIFO, the stored data can be read out by performing a burst read on the register (0x24) FIFO_DATA. The data is stored in units called frames.

2.5.1.1 Frame rates

The frame rate for the FIFO is defined by the maximum output data rate of the sensors enabled for the FIFO via the Register (0x46-0x47) FIFO_CONFIG. If pre-filtered data are selected in Register (0x45) FIFO_DOWNS, a data rate of 6400 Hz for the gyroscope and 1600 Hz for the accelerometer is used.

The frame rate can be reduced further via downsampling (Register (0x45) FIFO_DOWNS). This can be done independently for each sensor. Downsampling just drops sensor data; no data processing or filtering is performed.

2.5.1.2 Frame format

When using the FIFO, the stored data can be read out by performing a burst read on the register (0x24) FIFO_DATA. The data will be stored in frames. The frame format is important for the software to appropriately interpret the information read out from the FIFO.

The FIFO can be configured to store data in either header mode or in headerless mode (see figure below). The headerless mode is usually used when neither the structure of data nor the number of sensors change during data acquisition. In this case, the number of storable frames can be maximized. In contrast, the header mode is intended for situations where flexibility in the data structure is required, e.g. when sensors runs at different ODRs or when switching sensors on or off on the fly during operation.

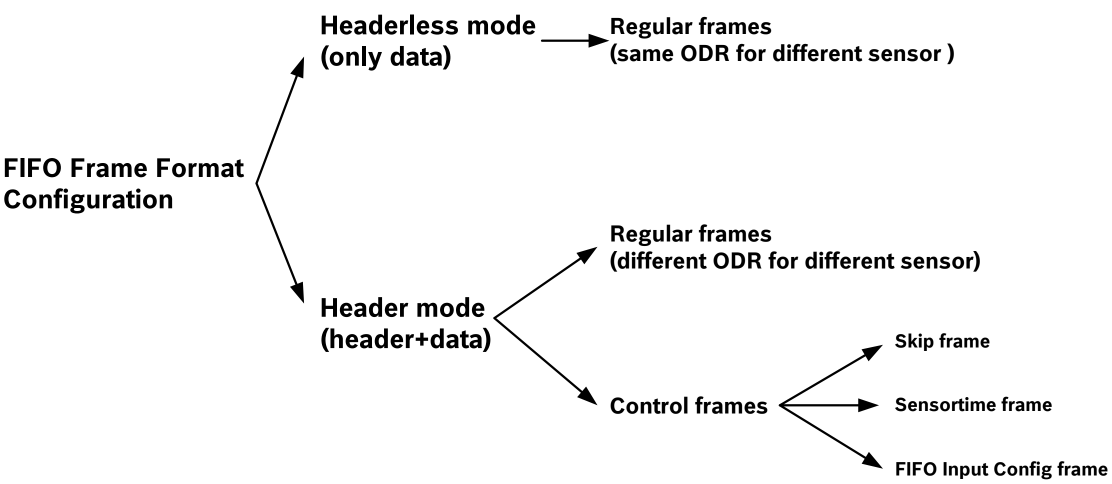

Figure 4: FIFO frame configurations

In **headerless mode** no header byte is used and the frames consist only of data bytes. The data bytes will always be sensor data. Only regular frames with the same ODR for all sensors are supported and no external interrupt flags are possible. This mode has the advantage of an easy frame format and an optimized usage of the 1024 bytes of FIFO storage. It can be selected by disabling fifo_header in Register (0x46-0x47) FIFO_CONFIG. In case of overreading the FIFO, non-valid frames always contain the fixed expression (magic number) 0x80 in the data frame.

In **header mode** every frame consists of a header byte followed by one or more data bytes. The header defines the frame type and contains parameters for the frame. The data bytes may be sensor data or control data. Header mode supports different ODRs for the different sensor data and external interrupt flags. This mode therefore has the advantage of allowing maximum flexibility of the FIFO engine. It is activated by enabling fifo_header in Register (0x46-0x47) FIFO_CONFIG.

2.5.1.3 Header byte format

The header format is shown below:

Bit	**7**	**6**	**5**	**4**
Content	fh_mode<1:0>		fh_parm<3:2>	

Bit	**3**	**2**	**1**	**0**
Read/Write	fh_parm<1:0>		fh_ext<1:0>	

The *fh_mode, fh_opt* and *fh_ext* fields are defined as

fh_mode<1:0>	**Definition**	**fh_parm <3:0>**	**fh_ext<1:0>**
0b10	Regular	Frame content	Tag of INT2 and INT1
0b01	Control	Control Opcode	
0b00	Reserved	Na	
0b11	Reserved	Na	

f_parm=0b0000 is invalid for regular mode, a header of 0x80 indicates an uninitialized frame.

2.5.1.4 Data bytes Format

When the FIFO is set to “headerless mode“, only sensor data will be saved into the FIFO (in the same order as in the data register). Any combination of accelerometer, gyroscope and external sensor data can be stored. External interrupt tags are not supported in headerless mode.

When the FIFO is set to “header mode“, the data byte format is different depending on the type of frame. There are two basic frame types, control frames and regular data frames. Each different type of control frame has its own data byte format. It can contain skipped frames, sensortime data or FIFO configuration information as explained in the following chapters. If the frame type is a regular frame (sensor data), the data byte section of the frame depend on how the data is being transmitted in this frame (as specified in the header byte section). It can include data from only one sensor or any combination of accelerometer, gyroscope and external sensor data.

2.5.1.5 Frame types

Regular frame (fh_mode=0b10)

Regular frames are the standard FIFO frames and contain sensor data. Regular frames can be identified by fh_mode set to 0b10 in the **header byte** section. The fh_parm frame defines which sensors are included in the data byte of the frame. The format of the fh_param is defined in the following table:

Name		**fh_parm<2:0>**		
Bit	3	2	1	0
Content	reserved	fifo_mag_data	fifo_gyr_data	fifo_acc_data

When fifo_<sensor x>_data is set to '1'('0'), data for sensor x is included (not included) in the data part of the frame.
The fh_ext<1:0> field is set when an external interrupt is triggered. External interrupt tags are configured using *int<x>_output_en* in Register (0x53) INT_OUT_CTRL. For details, please refer to chapter 2.5.2.4.

The **data byte** part for regular data frames is identical to the format defined for the Register (0x04-0x17) DATA. If a header indicates that not all sensors are included in the frame, these data are skipped and do not consume space in the FIFO.

Control frame (fh_mode=0b01):
Control frames, which are only available in header mode, are used for special or exceptional information. All control frames contribute to the *fifo_byte _counter* in Register (0x22-0x23) FIFO_LENGTH. In detail, there are three types of control frame, which can be distinguished by the *fh_parm* field:

Skip frame (fh_parm=0b000):
In case of a FIFO overflow, a skip frame is prepended to the FIFO content when the next readout is performed. A skip frame indicates the number of skipped frames since the last readout.
In the header byte of a skip frame, fh_mode equals 0b01 (since it is a control frame) and the fh_param equals 0b000 (indicating skip frame). The data byte part of a skip frame consists of one byte and contains the number of skipped frames. When more than 0xFF frames have been skipped, 0xFF is returned.

Sensortime frame (fh_parm=0b001):
If the sensortime frame functionality is activated (see description of Register (0x46-0x47) FIFO_CONFIG) and the FIFO is overread, the last data frame is followed by a sensortime frame. This frame contains the BMI160 timestamp content corresponding th the time at which the last data frame was read.
In the header byte of a sensortime frame, fh_mode = 0b01 (since is a control frame) and fh_param = 0b001 (indicating sensortime frame). The data byte part of a sensortime frame consists of 3 bytes and contains the 24-bit sensortime. A sensortime frame does not consume memory in the FIFO.

FIFO_input_config frame (fh_parm=0b010):

Whenever the configuration of the FIFO input data sources changes, a FIFO input config frame is inserted into the FIFO in front of the data to which the configuration change is applied.
In the header byte of a skip frame, fh_mode = 0b01 (since it is a control frame) and fh_param = 0b010 (indicating FIFO_input_config frame). The data byte part of a FIFO_Input_Config Frame consists of one byte and contains data corresponding to the following table:

Bit	**7**	**6**	**5**	**4**
Content	reserved			

Bit	**3**	**2**	**1**	**0**
Read/Write	gyr_range_ch	gyr_conf_ch	acc_range_ch	acc_conf_ch

gyr_range_ch:	A change in Register (0x43) GYR_RANGE becomes active.
gyr_conf_ch:	A change in Register (0x42) GYR_CONF or gyr_fifo_filt_data or gyr_fifo_downsampling in Register (0x45) FIFO_DOWNS becomes active.
acc_range_ch:	A change in Register (0x41) ACC_RANGE becomes active.
acc_conf_ch:	A change in Register (0x40) ACC_CONF or acc_fifo_filt_data or acc_fifo_downsampling in Register (0x45) FIFO_DOWNS becomes active.

2.5.2 FIFO conditions and details

2.5.2.1 Overflows

In the case of overflows the FIFO will overwrite the oldest data. A skip frame will be prepended at the next FIFO readout if the available FIFO space falls below the maximum size frame.

2.5.2.2 Overreads

If more data bytes are read from the FIFO than valid data bytes are available, ‘0x80’ is returned. Since a header ‘0x80’ indicates an invalid frame, the SW can recognize the end of valid data. After the invalid header the data is undefined. This is valid in both headerless and header mode. In addition, if header mode and the sensortime frame are enabled, the last data frame is followed by a sensortime frame. After this frame, a 0x80 header will be returned that indicates the end of valid data.

2.5.2.3 Partial frame reads

When a frame is only partially read through, it will be repeated within the next reading operation (including the header).

2.5.2.4 FIFO synchronization with external events

External events can be synchronized with the FIFO data by connecting the event source to one of the BMI160 interrupt pins (which needs to be configured as an input interrupt pin). External events can be generated e.g. by a camera module. Each frame contains the value of the interrupt input pin at the time of the external event.

The fh_ext<1:0> field is set when an external interrupt is triggered. External interrupt tags are configured using *int<x>_output_en* in Register (0x53) INT_OUT_CTRL.

2.5.2.5 FIFO Reset

A reset of the BMI160 is triggered by writing the opcode 0xB0 “fifo_flush“ to the Register (0x7E) CMD. This will clears all data in the FIFO while keeping the FIFO settings unchanged.

Automatic resets are only done in two exceptional cases where the data would not be usable without a reset:

- a sensor is enabled or disabled in headerless mode,
- a transition between headerless and headermode occurred.

2.5.2.6 Error Handling

In case of a configuration error in Register (0x46-0x47) FIFO_CONFIG, no data will be written into the FIFO and the error is reported in Register (0x02) ERR_REG.

2.6 Interrupt Controller

There are 2 interrupt output pins, to which thirteen different interrupt signals can be mapped independently via user programmable parameters.

Available interrupts supported by accelerometer in normal mode are:

- **Any-motion (slope) detection** for motion detection
- **Significant motion**
- **Step detector**
- **Tap sensing** for detection of single or double tapping events
- **Orientation detection**
- **Flat detection** for detection of a situation when one defined plane of the sensor is oriented parallel to the earth’s surface
- **Low-g/high-g** for detecting very small acceleration (e.g. free-fall) or very high acceleration (e.g. shock events)
- **No/slow-motion** detection for triggering an interrupt when no (or slow) motion occurs during a certain amount of time

In addition to that the common interrupts for accelerometer and gyroscope are

- **Data ready (“new-data”)** for synchronizing sensor data read-out with the MCU / host controller
- **FIFO full / FIFO watermark** allows FIFO fill level and overflow handling.

All Interrupts are available only in normal (low-noise) and low-power modes, but not in suspend mode. In suspend mode only the status (like orientation or flat) can be read out, but no interrupt will be triggered (unless latching is used).

If latching is used the interrupts (as well as the interrupt status) will be latched also in suspend mode, but no new interrupts will be generated.

Input Interrupt Pins: For special applications (e.g. PMU Trigger, FIFO Tag) interrupt pins can be configured as input pins. For all other cases (standard interrupts), the pin must be configured as an output.