shimmer™
DISCOVERY IN MOTION

IMU User Guide

Revision 1.4

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1. Introduction

This document is an accompaniment to the following inertial measurement units (IMUs) from Shimmer:

- The *Shimmer3 Wireless Sensor Unit* contains accelerometers, a gyroscope and a magnetometer to enable a complete 9 DoF solution. There are two accelerometers, providing the option for wide range or low noise measurements, allowing the user to tailor the configuration to the needs of the application.
- The *Shimmer2r Wireless Sensor Unit* includes an accelerometer, which measures and records acceleration due to all forces acting on the device.
- The *Shimmer Gyro IMU* daughterboard has a rate gyroscope, which measures angular velocity
- The *Shimmer 9DoF IMU* daughterboard has a both a gyroscope to measure angular velocity and a magnetometer to measure magnetic field, which, combined with the accelerometer on the baseboard, can give a kinematics solution with 9 degrees of freedom (DoF).

It is intended that users refer to this document to help getting started with measuring and processing kinematic data using the Shimmer platform. The document contains theoretical and practical information regarding kinematic signals and sensors, along with a brief description of some common applications for these signals. It also includes technical information about the board layouts and signal quality specifications. Please refer to the Table of Contents on the previous page to find the parts of this document that are most relevant to your needs.

2. General Information

2.1. Pre-Requisites

- *A Shimmer 3*, *Shimmer 2*, *Shimmer 2r** device programmed with appropriate firmware. For example for Shimmer 3, *LogAndStream* (v0.6.0 or greater) can be used to log data or stream data over Bluetooth while *SD Log* (v0.12.0 or greater) can be used to log data to the SD card; both are available for download from www.shimmersensing.com. For Shimmer 2r, *BtStream* (v1.2.0 or greater) can be used to stream data over Bluetooth while *SD Log* (v1.6 or greater) can be used to log data to the SD card.
- If using *Shimmer2* or *Shimmer2r*, the following IMU daughterboards are optional:
    - A *Shimmer Gyro IMU* daughterboard.
    - A *Shimmer 9DoF IMU* daughterboard.

3. Inertial Measurement Units

This sections provides a brief introduction to IMUs (sometimes known as kinematic sensors) and the signals that they measure.

3.1. Accelerometer

The acceleration, $\underline{a}$, of a body can be defined as its rate of change of velocity and it is directly proportional to the forces, $\underline{F}$, acting on the body:

$$\underline{a} \propto \underline{F}.$$

An accelerometer is a device which measures acceleration due to all forces acting on the device. Forces acting on a device include both the gravitational force due to the mass of the earth as well as any inertial forces which may be applied to the device.

The two primary components of acceleration are, thus, *inertial* and *gravitational* acceleration. Thus, the total acceleration, $\underline{a}_T$, measured by the device is the vector sum of these components:

$$\underline{a}_T = \underline{a}_I + \underline{g},$$

where $\underline{a}_I$ is the inertial component and $\underline{g}$ is the gravitational component.

Inertial acceleration

Inertial acceleration occurs due to the application of a force other than gravity to a body. Unless a body is completely motionless or moving with a constant velocity, there are inertial forces acting on it. These forces give rise to inertial acceleration. This acceleration is defined as the rate of change of velocity of the body in motion. It is measured in units of m/s^2.

Acceleration due to gravity

Gravity is a natural phenomenon by which physical bodies attract each other with a force proportional to their masses. Gravity is most familiar as the agent that gives weight to objects with mass and causes them to fall to the ground when dropped.

The units of gravity are m/s^2. Thus, it is a form of acceleration and is measured by an accelerometer. When an accelerometer is completely stationary (i.e. there is no inertial acceleration acting on the device), it measures a constant acceleration equal in magnitude to the acceleration due to gravity (9.81 m/s^2 approx). This is often referred to in units labelled “g”, where 1 g ≈ 9.81 m/s^2.

It is a common misconception to assume that the direction of the gravity vector measured by an accelerometer is vertically downwards; this is incorrect. In fact, the measured vector of acceleration due to gravity points vertically upwards from the Earth’s surface.

A simple example to help you remember that this is the case is the observation that an accelerometer in free-fall records an acceleration of zero. In this case, the downward inertial acceleration due to motion equals the upward gravitational acceleration.

A good way to understand why the measured acceleration due to gravity points in an upward direction is to imagine that an accelerometer is a hollow cube with a ball inside, as illustrated in Figure 3-1. The six faces of the cube will measure acceleration in the positive and negative directions of the three sensing axes as illustrated by the X, Y and Z directions in the figure. To begin with, imagine that the ball is weightless – it is suspended in the middle of the hollow cube and not affected by gravity.

In Figure 3-1, the accelerometer has no forces acting on it – i.e. no inertial acceleration due to movement and no gravitational acceleration. The acceleration measured in each of the axes, a_x, a_y and a_z, will be zero. This is the case when the device is in free-fall.

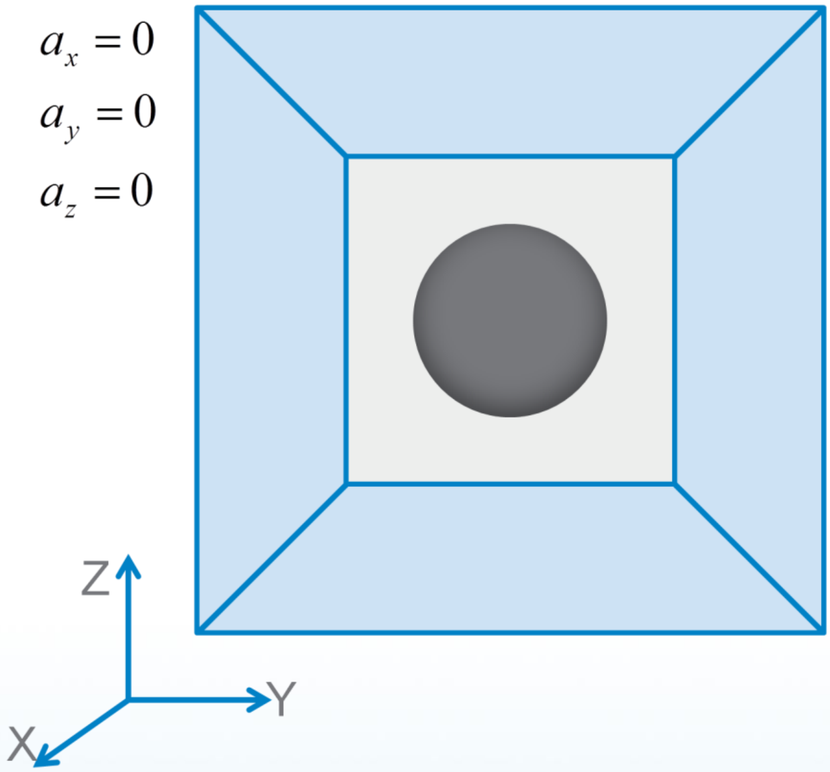

Figure 3-1 Accelerometer in free-fall

Now, continuing to ignore gravity by assuming that the ball is weightless, imagine that the cube is moved to the right; i.e. acceleration in the positive Y-direction, as shown in Figure 3-2. The accelerometer will detect acceleration in the positive Y-direction by feeling the suspended ball press against the *opposite* face of the box.

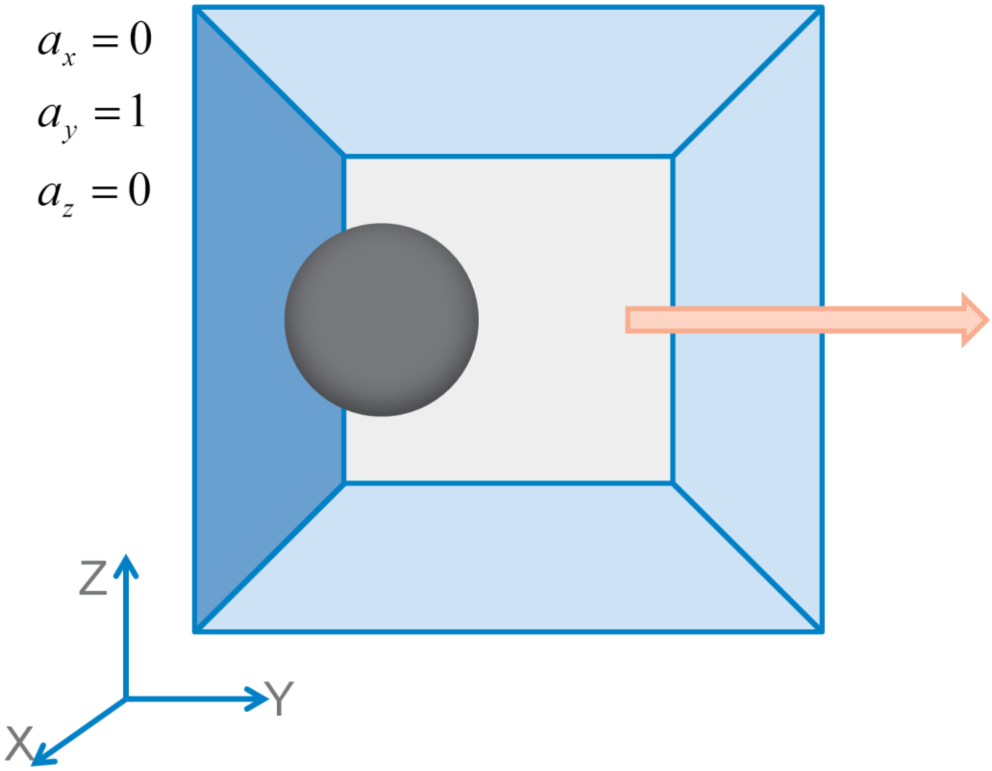

Figure 3-2 Acceleration in positive Y-direction

Now, let's lift the assumption that the ball is weightless and include the effect of gravity. If the accelerometer is motionless, the ball will rest on the bottom face of the hollow cube. Just as you have seen that positive acceleration in the Y-axis was detected by the ball pressing against the opposite face, in this case, positive acceleration due to gravity in the Z-axis will be detected by the ball pressing against its opposite face. Thus, it is clear that acceleration due to gravity, measured by the accelerometer, points in an upward direction.

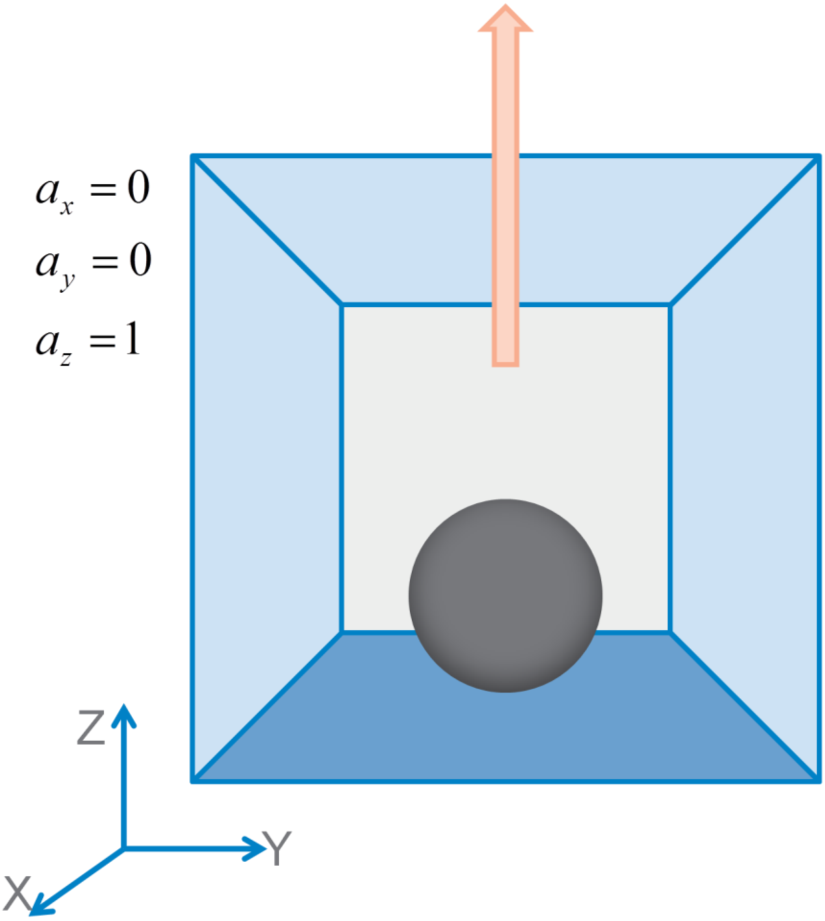

Figure 3-3 Accelerometer measuring gravity in upward positive Z-direction

Measuring 3D Acceleration

The *Shimmer3* is equipped with tri-axial accelerometers (as is the *Shimmer2r*). The default representation of its reference axes, as assumed in Shimmer applications, is arranged as shown in Figure 9-2. Thus, the acceleration measured by the Shimmer device has three components, one in each of the X-, Y- and Z-axes.

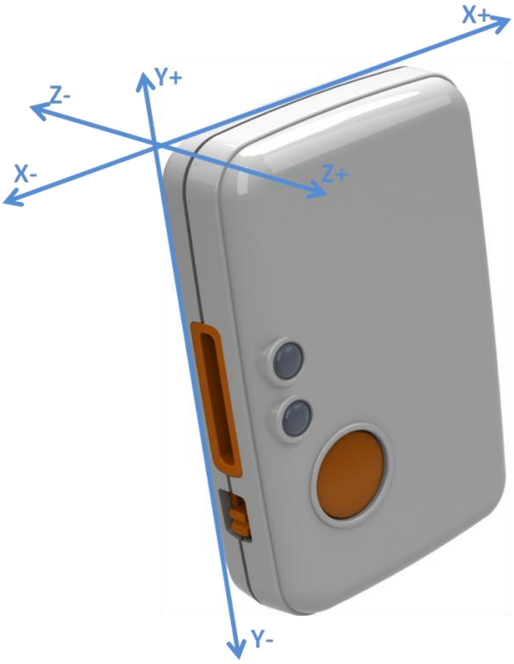

Figure 3-4 Shimmer3 default axis directions

To understand how the acceleration is distributed across the axes, we consider, first, a single axis (uni-axial) accelerometer.

Uni-axial accelerometer

A uni-axial accelerometer measures the sum of the inertial acceleration component and gravitational acceleration component acting along its single measuring axis. The left side of Figure 3-5 shows a uni-axial accelerometer, with measurement axis, $\underline{a}_x$, attached to a leg segment. There is an inertial acceleration of $\underline{a}_I$ acting on the segment, as illustrated. The gravitational acceleration vector, $\underline{g}$, is also included in the figure.

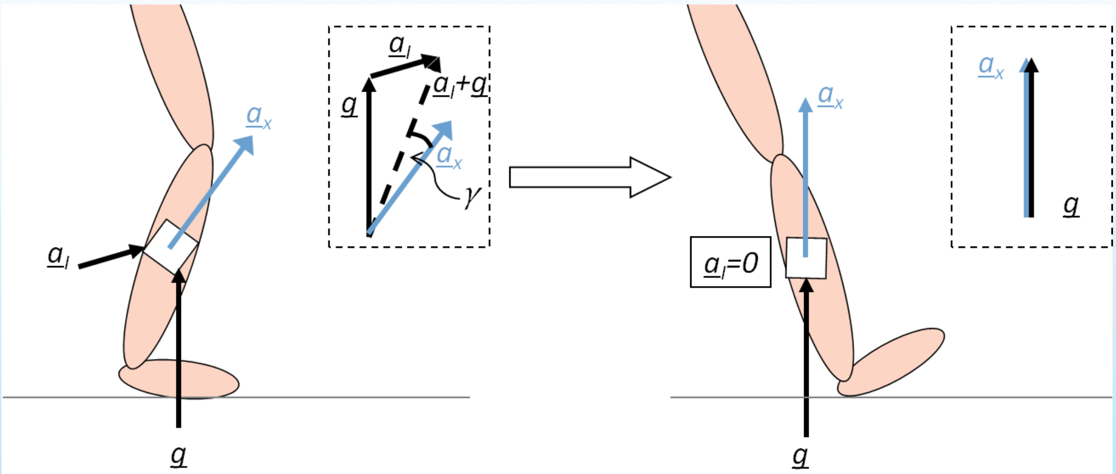

Figure 3-5: Uni-axial accelerometer attached to a leg segment

In the insert at the left side of the figure, the sum of the inertial and gravitational acceleration vectors is illustrated by a dashed arrow, $\underline{a}_I + \underline{g}$. This vector is the total acceleration acting on the device. The sensor axis, $\underline{a}_x$, measures a component of this acceleration, whose magnitude is given by:

$$\underline{a}_x = \left\| \underline{a}_I + \underline{g} \right\| \cos(\gamma)\,,$$

where $\|x\|$ denotes the magnitude of the vector $\underline{x}$[1], and γ is the angle between the measurement axis, $\underline{a}_x$, and the total acceleration vector, $\underline{a}_I + \underline{g}$. Alternatively, $\underline{a}_x$ can be written as:

$$\underline{a}_x = a_I \cos(\theta_x) + g \cos(\varphi_x)\,,$$

where θ_x and φ_x are the angles that the axis, $\underline{a}_x$, makes with the inertial acceleration vector, $\underline{a}_I$, and the gravity vector, $\underline{g}$, respectively, $a_I = \left\| \underline{a}_I \right\|$ is the magnitude of inertial acceleration vector and $g = 9.81$ m/s^2 is the magnitude of the gravity vector.

In the right side of Figure 3-5, the leg segment (and, hence, the uni-axial accelerometer) has moved and come to rest in the position shown. In this case, the inertial acceleration is zero ($\underline{a}_I = 0$). Thus, gravity is the only acceleration component felt by the device. Due to the rotation of the sensor cause by the movement of the leg segment, the accelerometer measurement axis is now perfectly aligned with the gravity vector. In this case, $\underline{a}_x = \underline{g}$, as illustrated in the insert on the right side of the figure.

Bi-axial accelerometer

A bi-axial accelerometer consists of two uni-axial accelerometers arranged at a right angle to one another, as illustrated in Figure 3-6. This device measures the sum of the inertial acceleration component and gravitational acceleration component acting along each of its two measuring axis. The bi-axial accelerometer in Figure 3-6 is measuring acceleration under the same conditions as described for Figure 3-5.

[1] The magnitude, $\|\underline{x}\|$, of a three dimensional vector, $\underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$, is given by:

$$\|\underline{x}\| = \sqrt{{x_1}^2 + {x_2}^2 + {x_3}^2}.$$

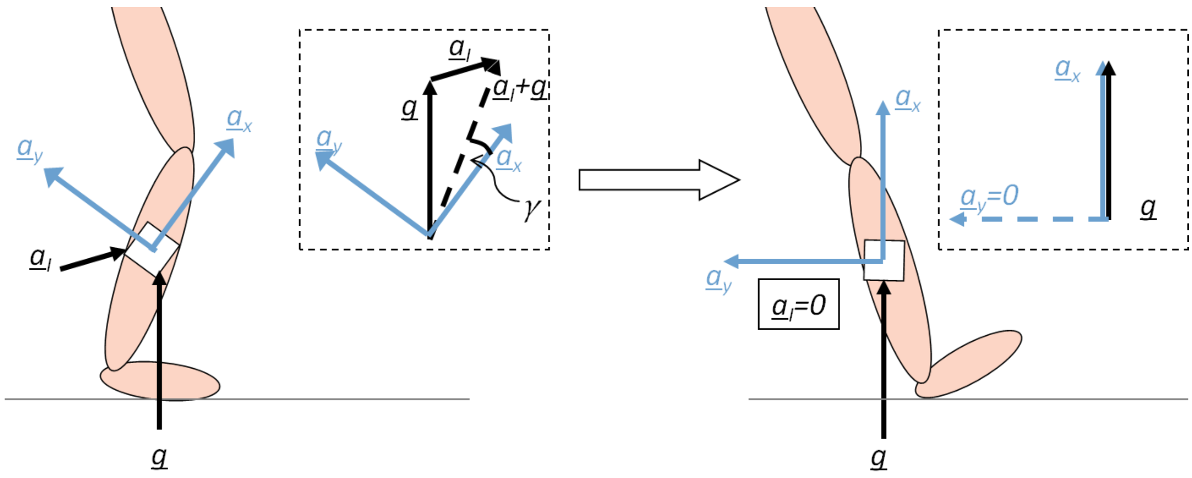

Figure 3-6: Bi-axial accelerometer attached to a leg segment

The insert at the left side of the figure shows the vector sum of the inertial and gravitational acceleration components, as in Figure 3-5. This time, the acceleration will be measured in two axes. However, the acceleration measured by the X-axis ($\underline{a}_x$) will be exactly the same as that measured by the uni-axial accelerometer in the same position; the two axes of the accelerometer act independently of each other. The Y-axis ($\underline{a}_y$) will measure the acceleration perpendicular to $\underline{a}_x$, whose magnitude is given by:

$$\underline{a}_y = \left\| \underline{a}_I + \underline{g} \right\| \sin(\gamma) \, ,$$

where γ is the angle between the measurement axis, $\underline{a}_x$, and the total acceleration vector, $\underline{a}_I + \underline{g}$, as described previously (note, that this angle is defined from the X-axis). Alternatively, $\underline{a}_y$ can be written as:

$$\underline{a}_y = a_I \cos(\theta_y) + g \cos(\varphi_y) \, ,$$

where θ_y and φ_y are the angles that the axis, $\underline{a}_y$, makes with the inertial acceleration vector, $\underline{a}_I$, and the gravity vector, $\underline{g}$, respectively.

Now, consider the right side of Figure 3-6, in which the inertial acceleration is zero and the X-axis is parallel to the gravity vector. In this situation, the Y-axis is perpendicular to the gravity vector (i.e. at an angle of 90°) and, thus, the Y-axis will measure $\underline{a}_y = 0$ because the gravity vector has no component perpendicular to itself. Indeed, the component of any vector acting perpendicular to the vector itself is always zero.

The total acceleration measured by the bi-axial accelerometer may be written as a vector:

$$\underline{a} = \begin{bmatrix} a_x \\ a_y \end{bmatrix} = \begin{bmatrix} \left\| \underline{a}_I + \underline{g} \right\| \cos(\gamma) \\ \left\| \underline{a}_I + \underline{g} \right\| \sin(\gamma) \end{bmatrix} = \begin{bmatrix} a_I \cos(\theta_x) + g \cos(\varphi_x) \\ a_I \cos(\theta_y) + g \cos(\varphi_y) \end{bmatrix} .$$

A bi-axial accelerometer can be used to measure the inclination angle of the body to which it is attached, if its measurement axes are located in the plane of the gravity vector and the only force acting on the device is gravity. In the case shown on the right-hand side of Figure 3-6, $\underline{a}_I = 0$ and the angle of inclination, γ, of the device, with respect to the gravity vector is given by:

$$\gamma = \tan^{-1}\left(\frac{a_y}{a_x}\right).$$

Tri-axial accelerometer

A tri-axial accelerometer is formed of three mutually orthogonal uni-axial accelerometers (i.e. three accelerometer components arranged such that each axis is at a right angle to the other two axes). As in the case of the uni-axial and bi-axial accelerometers, each axis measures a certain proportion of both the gravitational acceleration and the inertial acceleration. The proportions measured by a given axis depend on the angles between that axis and the directions of the acceleration components. The total acceleration vector can be written as:

$$\underline{a} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} a_I \cos(\theta_x) + g\cos(\varphi_x) \\ a_I \cos(\theta_y) + g\cos(\varphi_y) \\ a_I \cos(\theta_z) + g\cos(\varphi_z) \end{bmatrix},$$

where the same notation that has previously been used for the X- and Y-axes is followed for the Z-axis.

3.2. Angular rate gyroscope

The angular velocity of a body can be described as the rate at which the object is rotating, in terms of both the speed of rotation and the axis about which it is rotating. A rate gyroscope can be used to measure angular velocity.

The *Shimmer3* is equipped with a tri-axial rate gyroscope to measure angular velocity in three dimensions. (For *Shimmer2r*, the *9DoF IMU daughterboard* or *Gyro IMU daughterboard* is required.) To understand what component of angular velocity each of the three axes measures, it is useful to, first, consider a uni-axial gyroscope.

Uni-axial rate gyroscope

A uni-axial rate gyroscope measures the angular velocity acting along a single measuring axis. Figure 3-7 shows a uni-axial gyroscope attached to a rotating plate, rotating with angular velocity $\underline{\omega}$, whose magnitude is ω and direction is perpendicular to the plate, as illustrated.

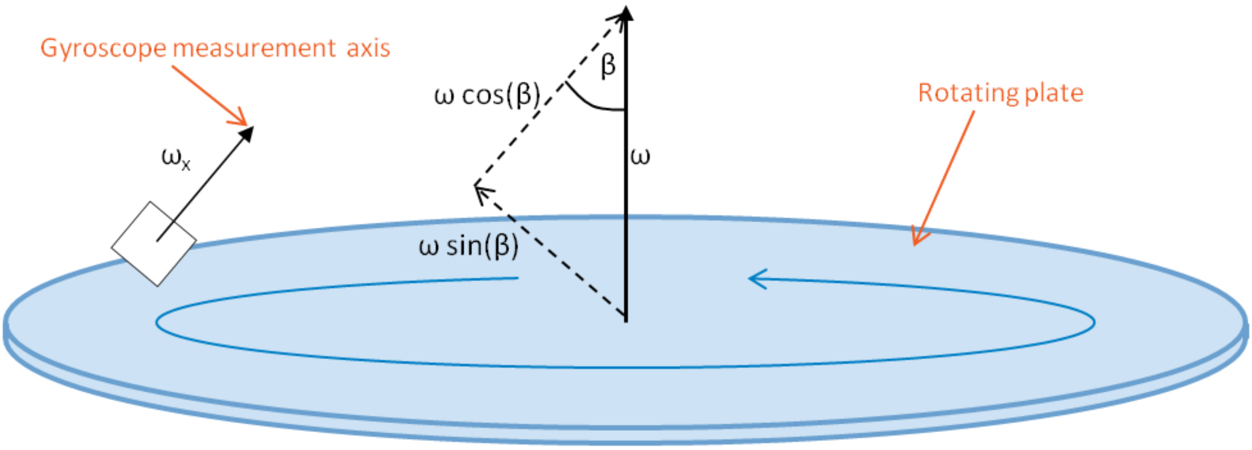

Figure 3-7: Uni-axial rate gyroscope attached to a rotating plate

The angular velocity measured by the gyroscope, whose measurement axis, ω_x, makes an angle, β, with the axis about which the plate is rotating, is given by:

$$\omega_x = \omega\cos(\beta),$$

where

ω_x is the magnitude of the angular velocity vector component along the measuring axis of the rate gyroscope,

β is the inclination of the measuring axis with respect to the angular velocity vector,

ω is the magnitude of the angular velocity acting on the sensor.

If the measurement axis is aligned parallel with the rotation axis, then the measured angular velocity will be equal to ω. If, on the other hand, the measurement axis is perpendicular to the rotation axis, then it will measure an angular velocity of zero.

Tri-axial rate gyroscope

A tri-axial rate gyroscope is formed by three orthogonal uni-axial rate gyroscopes. A 3-dimensional angular velocity vector is obtained from a tri-axial rate gyroscope. The angular velocity vector measured by a tri-axial rate gyroscope is given by:

$$\underline{\omega} = \begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix} = \begin{bmatrix}\omega\cos(\beta_x)\\ \omega\cos(\beta_y)\\ \omega\cos(\beta_z)\end{bmatrix},$$

where β_x, β_y and β_z are the angles that the measurement axes, ω_x, ω_y and ω_z make with the rotation axis, respectively.

3.3. Magnetometer

Magnetic fields describe the influence of electric currents and magnetic materials on objects around them. The Earth has its own permanent magnetic field whose direction runs from the magnetic

South pole to the magnetic North pole and which influences all magnetic objects. This magnetic field can be exploited to determine the heading of an object, using a compass. Large metal objects and sources of electromagnetic interference (such as lights or electronic devices) can distort the local effect of the Earth's magnetic field, resulting in heading errors, so it is best to use compasses as far away from these sources of interference as possible.

A magnetometer is a sensor which is used to measure the direction and/or the strength of the local magnetic field. If the only magnetic field acting on the magnetometer is the Earth's magnetic field, then it can be used as a compass to determine the direction in which the sensor is facing, relative to the Earth's magnetic North pole.

The Earth's magnetic field does not act parallel to the Earth's surface. Instead, there is a magnetic inclination (also known as magnetic dip) angle, which causes the compass needle to point upwards or downwards (relative to the horizontal plane of the Earth's surface), depending on where in the world the compass is. At the magnetic equator, the angle is zero and the magnetic field does act exactly parallel to the Earth's surface. In the Northern hemisphere, the North end of the compass needle begins to point downwards more and more as one approaches the magnetic North Pole. In the Southern hemisphere, the North end of the compass needle points increasingly upwards as one approaches the magnetic South pole. When using a magnetometer to measure the magnetic field in three dimensions, the appropriate magnetic inclination angle for the geographic location should be taken into account. For example, in Dublin, Ireland, the angle is approximately 68°.

The *Shimmer3* is equipped with a tri-axial magnetometer to measure the local magnetic field in three-dimensions. (For *Shimmer2r*, the *9DoF IMU daughterboard* is required,) To understand how the magnetic field measurement is distributed over the three sensing axes, it is useful to, first, consider a uni-axial magnetometer.

Uni-axial magnetometer

A uni-axial magnetometer measures the magnetic field vector acting along its measuring axis. Figure 3-8 shows a uni-axial magnetometer attached to a leg segment.

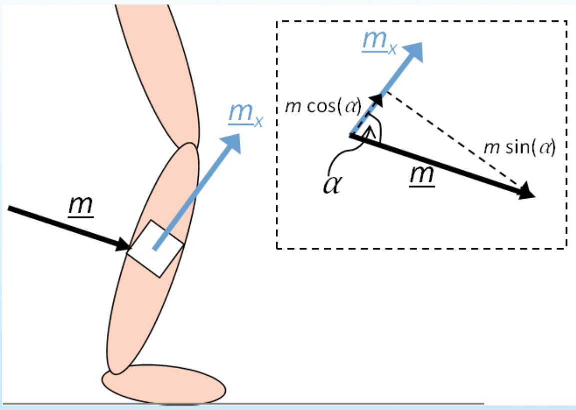

Figure 3-8: Uni-axial magnetometer attached to a leg segment

The magnetic field measured by the magnetometer, whose measurement axis, $\underline{m_x}$, makes an angle, α, with the magnetic field vector, $\underline{m}$, is given by:

$$m_x = m\cos(\alpha),$$

where

m_x is the magnitude of the magnetic field vector component along the measuring axis of the magnetometer,

α is the angle between the magnetometer measuring axis and the magnetic field vector,

m is the magnitude of the magnetic field acting on the sensor.

If the measurement axis is aligned parallel with the magnetic field vector, then the measured magnetic field component will be equal to m. If, on the other hand, the measurement axis is perpendicular to the magnetic field vector, then it will measure a magnetic field of zero.

Bi-axial magnetometer

A bi-axial magnetometer consists of two uni-axial magnetometer components arranged perpendicular to each other. The magnetic field component measured by the X-axis remains unchanged from the uni-axial case. The component measured by the Y-axis is given by:

$$m_y = m\sin(\alpha),$$

where α is the same angle that was defined previously and illustrated in Figure 3-8.

A bi-axial magnetometer can be used to measure the inclination angle of the body to which it is attached, if its measurement axes are located in the plane of the magnetic field vector. In this case, the heading angle, α, of the device, with respect to the magnetic field vector is given by:

$$\alpha = \tan^{-1}\left(\frac{m_y}{m_x}\right).$$

If the local magnetic field is equal to the Earth's magnetic field (i.e. there are no sources of interference), then α is the heading angle of the sensor, relative to the Earth's magnetic North pole.

Tri-axial magnetometer

A tri-axial magnetometer is formed by three orthogonal uni-axial magnetometers. A 3-dimensional magnetic field vector is obtained from a tri-axial magnetometer. The magnetic field vector, $\underline{m}$, measured by a tri-axial magnetometer is given by:

$$\underline{m} = \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} m\cos(\alpha_x) \\ m\cos(\alpha_y) \\ m\cos(\alpha_z) \end{bmatrix},$$

where α_x, α_y and α_z are the angles that the measurement axes, m_x, m_y and m_z make with the magnetic field vector, $\underline{m}$, respectively.

4. Inertial Sensor Signals

4.1. The IMU Signal

IMUs, like all sensors, are subject to noise and other errors, like offset bias and axis alignment errors. Furthermore, sensor measurements are limited to values in a finite range, whilst most physical phenomena have an infinite range. Also, if the output of the sensor is digital, quantisation introduces noise in the measurements. Thus, the value measured by any sensor is not exactly equal to the value of the phenomenon being measured.

Uni-axial sensor measurement

For a uni-axial sensor, if the value of the sensed phenomenon along the sensor measurement axis is υ, then the sensor output, Υ, can be described by:

$$\Upsilon = k\upsilon + b + n,$$

where k is the sensor scale factor, b is the offset bias and n is noise. Ignoring noise, which is usually random and cannot be estimated, the scale factor is the value by which the sensor output will increase for an increase of one unit in the sensed phenomenon and the offset bias is the value of the sensor output when the sensed phenomenon is equal to zero; these quantities can both be estimated by calibrating the sensor[2].

Tri-axial sensor measurement

Ideally, a tri-axial IMU should consist of three mutually orthogonal uni-axial sensors (i.e. each axis makes a right angle with the other two axes). However, real sensors tend to be subject to misalignment errors due to minor errors in the placement of sensors, meaning that the sensor axes are not precisely orthogonal to each other. Also, the assumed orientation of the sensor may not be aligned with its true orientation when it is placed inside its casing.

The result of this misalignment error is that it is necessary to define a rotation operation which relates the assumed sensitivity axes with the actual sensitivity axes of the sensor. In fact, the user may define any set of assumed sensitivity axes and calculate the required rotation during the calibration process[2]. The rotation can be easily described by a rotation matrix, R.

For a tri-axial sensor, if the value of the sensed phenomenon vector is $\underline{\upsilon}$, then the sensor output, $\underline{\Upsilon}$, can be described by:

$$\underline{\Upsilon} = KR\underline{\upsilon} + \underline{b} + \underline{n},$$

where

[2] For more detailed information on the calibration of kinematic sensors, please refer to the *Shimmer 9Dof Calibration Application* and the associated User Manual and Tutorial videos, available from www.shimmersensing.com.

$\underline{\Upsilon} = \begin{bmatrix} \Upsilon_x \\ \Upsilon_y \\ \Upsilon_z \end{bmatrix}$ is the sensor output,

$\underline{\upsilon} = \begin{bmatrix} \upsilon_x \\ \upsilon_y \\ \upsilon_z \end{bmatrix}$ is the vector value of the sensed phenomenon,

$K = \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix}$ is the diagonal matrix of sensor axis scale factors,

$R = \begin{bmatrix} r_{x'x} & r_{x'y} & r_{x'z} \\ r_{y'x} & r_{y'y} & r_{y'z} \\ r_{z'x} & r_{z'y} & r_{z'z} \end{bmatrix}$ is the rotation matrix which defines the actual sensor axes (x, y and z) with respect to the assumed sensitivity axes (x', y' and z'),

$\underline{b} = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}$ is the offset bias vector, and

$\underline{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}$ is the noise vector.

The average noise affecting the kinematic sensors on the *Shimmer3*, *Shimmer2r*, *Gyro IMU daughterboard* and *9DoF IMU daughterboard* is summarised in Section 6.1 and Appendix 9.1.

4.2. Kinematic Parameters

The complete kinematics of a body in three-dimensional space can be described using the following 15 variables (Winter, 1990):

- Linear displacement of body's centre of mass (x, y and z),
- Linear velocity of the body's centre of mass ($\dot{x}$, $\dot{y}$ and $\dot{z}$),
- Linear acceleration of the body's centre of mass ($\ddot{x}$, $\ddot{y}$ and $\ddot{z}$),
- Angular displacement of the body in two planes (θ_{xy}, θ_{yz}),
- Angular velocity of the body in two planes (ω_{xy}, ω_{yz}),
- Angular acceleration of the body in two planes (α_{xy}, α_{yz}).

These parameters can be estimated using IMUs with varying levels of difficulty. For example, linear acceleration and angular velocity can be directly estimated from the accelerometer and gyroscope observations, respectively. Angular acceleration can be determined by calculating the derivative of angular velocity, taking care to deal with high frequency noise introduced by the derivative. Angular displacement can be instantaneously estimated using a stationary accelerometer and/or magnetometer, as outlined in Sections 3.1 and 3.3, whilst sensor fusion of at least accelerometer and gyroscope is required to accurately estimate continuous angular displacement for moving bodies. Linear velocity is the integral of linear acceleration, but measures to eliminate errors due to accelerometer offset bias and noise must be taken to ensure accurate estimation. Finally, estimation of linear displacement requires complicated sensor fusion algorithms; this topic is briefly discussed in Section 5.2.

4.3. Coordinate Systems

The coordinate system used to define the variables above must be defined relative to some reference system; if the coordinate system is defined relative to a constant external reference system, then the reference is known as the global system. One of most commonly used global reference systems is the Earth's {North, East, Down} frame. If, on the other hand, the coordinate system for one body is described relative to the coordinate system of another body (which may itself be variable), then it is known as a relative system.

For example, imagine that two sensors are attached to a person's arm, with one below the elbow and the other above the elbow, and the person moves his/her arm whilst walking through a building. The relative kinematics describe the linear and angular displacements, velocities and accelerations between the two arm segments, regardless of where in the building the person is, in which direction they are facing, or whether they are moving or still. The global kinematics describe the linear and angular displacement, velocity and acceleration of each sensor, independent of the other sensor, describing where in the building the person is, etc.

The angular displacement of one coordinate system, relative to another system, can be described by a rotation matrix of dimension, 3x3. For more detail on how to construct this matrix, see (Craig, 1989), for example. There are also other formats for describing the angular displacement between to coordinate systems, including angle-axis, Euler angles and quaternions. The preference for one format over another depends largely on the application and its storage and computational requirements and limitations.

5. Applications of IMUs

The following are examples of problems for which IMU-based solutions are often sought. A very brief outline of the suitability of IMUs for these problems is provided, along with some references to help the new user to get started with investigating these topics. Please note that solutions to these applications are not directly supported by Shimmer and the information below is intended as a starting point for the new user, unfamiliar with the relevant literature.

5.1. Gait analysis

Inertial sensors are ideal for measuring the temporal parameters of gait (stride time, step time, stance time). The following paper describes methods by which this can be achieved using a gyroscope (Greene, McGrath, O'Neill, O'Donovan, Burns, & Caulfield, 2010). Determining spatial parameters (e.g. step length and stride length) from inertial sensors is non-trivial due to the problems of drift associated with double integration of the noisy accelerometer signal. Examples of publications which attempt to estimate the spatio-temporal parameters using inertial sensors include (Doheny, Foran, & Greene, 2010), (Bugané, et al., 2012), (Zijlstra, 2004), (Sabatini, Martelloni, Scapellato, & Cavallo, 2005).

5.2. Displacement estimation

Noise and other error sources (e.g. offset bias) in accelerometers mean that it is not possible to accurately estimate displacement by direct double integration of accelerometer observations alone. Indeed, the problem of estimating displacement is not a trivial one and there is vast literature available on the subject. A recently published review of displacement estimation systems (Harle, 2013) and the references therein provide a good starting point for understanding the subject.

Most successful displacement estimation systems rely on fusion of multiple sensors – including accelerometers, gyroscopes and magnetometers, as well as video, GPS, and infra-red position sensors, to name just a few examples. They also involve elaborate processing of the inertial observations, with Kalman filters and their derivatives being among the most popular approaches, e.g. (Won, Melek, & Golnaraghi, 2010). Other *ad hoc* approaches, such as the use of zero velocity updates for walking data (Skog, Nilsson, & Handel, 2010), or constrained sensor placement (Yadav & Bleakley, 2011) can also help to limit the growth of errors. The required level of accuracy and, more significantly, the length of time over which accurate continuous displacement estimation is needed, determines how complicated the solution needs to be.

5.3. Orientation estimation

Estimation of the orientation of an object in three-dimensional space can be calculated using IMUs. Using accelerometers and gyroscopes, the orientation of the object, relative to its initial orientation, can be determined. For a full orientation solution, estimating absolute instead of relative orientation, magnetometers are also required. There are many such algorithms in the literature - an example of both a relative algorithm and an absolute orientation algorithm can be found in (Madgwick, Harrison, & Vaidyanathan, 2011).

5.4. Fall detection

Fall detection is a common application of IMUs in healthcare, with concerns about an ageing population generating significant research interest in recent years. A basic but over-simplistic method for detecting falls using an accelerometer alone, would be to calculate the magnitude of the measured acceleration and compare this to a threshold to detect a large spike due to an impact. A recent review on fall detection (Mubashir, Shao, & Seed, 2013) contains a section on various accelerometer-based methods and a comprehensive list of references. Other articles describing how IMUs can be used for fall detection include (Bourke, et al., 2010), (Bourke, O'Donovan, & OLaighin, 2008), (Nyan, Tay, & Murugasu, 2008) and the references therein.

6. Practical Usage Considerations

6.1. Shimmer3 Capabilities

Low Noise Accelerometer

The output of the low noise accelerometer device on the *Shimmer3* is analog. A KXRB5-2042 device from Kionix is used. The following approximate values apply to this device:

- Zero-output: 1.5 V.
- Full scale range: ±2.0 g.
- Sensitivity: 600 mV/g.

Please refer to the manufacturer's datasheets for detailed information.

Wide Range Accelerometer

The output of the wide range accelerometer device on the *Shimmer3* is digital. An LSM303DLHC device from STMicro is used (this chip also gives magnetic sensing output). The following approximate values apply to this device:

- Full scale range: ±2.0 g; ±4.0 g; ±8.0 g; ±16.0 g.
- Sensitivity (LSB/g): 1000 (±2.0 g); 500 (±4.0 g); 250 (±8.0 g); 83.3 (±16.0 g).
- Output: 16 bit output[3].

Please refer to the manufacturer's datasheets for detailed information.

Gyroscope

The output of the gyroscope device on the *Shimmer3* is digital. The gyroscope on the MPU-9150 chip from Invensense is used. The following approximate values apply to these devices:

- Full scale range (deg/sec): ±250; ± 500; ±1000; ±2000.
- Sensitivity (LSB/(deg/sec)): 131 (±250); 65.5 (±500); 32.8 (±1000); 16.4 (±2000).
- Output: 16 bits.

Please refer to the manufacturer's datasheets for detailed information.

Magnetometer

The output of the magnetometer device on the *Shimmer3* is digital. An LSM303DLHC device from STMicroelectronics is used (this chip also gives wide range accelerometer output). The following approximate values apply to this device:

- Full scale range (Ga): ±1.3; ±1.9; ±2.5; ±4.0; ±4.7; ±5.6; ±8.1.
- Sensitivity (X,Y/Z) (LSB/Ga): 1100/980 (±1.3); 855/760 (±1.9); 670/600(±2.5); 450/400 (±4.0); 400/355(±4.7); 330/295 (±5.6); 230/205 (±8.1).

[3] Note that the LSM303DLHC accelerometer provides 12-bit resolution if HR mode is enabled and 10-bit resolution otherwise. The data is output in 16-bit format.

- Output: 16 bits[4].

Please refer to the manufacturer's datasheets for detailed information.

6.2. Noise Specifications

Table 1 shows the noise performance that can be expected at varying signal bandwidths for the IMU devices on a *Shimmer3* unit. The sampling rate in each case was 500 Hz and a low-pass filter was used to vary the bandwidth.

Bandwidth (Hz)	50	100	250
Low Noise Accelerometer RMS noise (m/s^2)	3.51×10^{-3}	5.09×10^{-3}	8.12×10^{-3}
Wide Range Accelerometer RMS noise (m/s^2)	18.6×10^{-3}	27.5×10^{-3}	37.2×10^{-3}
Gyroscope RMS noise (deg/s)	0.0322	0.0481	0.0785
Magnetometer RMS noise (normalised local flux)	0.0050	0.0081	0.0129

Table 1 : Measured RMS noise for Shimmer3

6.3. Safety Considerations

None.

6.4. Firmware

Developers should leverage the driver and test application code in the Shimmer github repository for *Shimmer3*. The *Shimmer User Manual* also includes useful information in the embedded firmware section.

[4] Note that the LSM303DLHC magnetometer provides 12-bit resolution. The data is output in 16-bit format.

7. FAQs

I have set the accelerometer range to ±1.5g; why can I get readings of up to 2g?

The selected range of the accelerometer is the range over which the measurements are reliable and performance is guaranteed by the sensor manufacturer. The sensor can operate beyond these limits but it is not recommendable to rely on out-of-range measurements.

I have configured my *Shimmer2/Shimmer2r* Wireless Sensor Unit to stream accel, gyro and mag data, but only the accel data looks meaningful - why is this?

Ensure that you have attached a *Shimmer 9DoF IMU* daughterboard to the *Shimmer* baseboard before you try to stream or log magnetometer data and that you have attached either a *9DoF IMU* daughterboard or a *Gyro IMU* daughterboard to the *Shimmer* baseboard before you try to stream or log gyroscope data.

Can I use IMUs to analyse gait?

IMUs are commonly used for gait analysis. Please see Section 5.1 for a brief discussion of this subject and some references to point you to recent literature on the topic.

Can I use accelerometer data to measure displacement?

This is a non-trivial problem. Please see Section 5.2 for a brief discussion of this problem and some references to point you to recent literature on the topic.

Why does a *Shimmer3* magnetometer axis sometimes read as -4096?

In the event of a data overflow on a magnetometer axis - as would be the case if the local magnetic field strength exceeds the configured magnetometer range - the corresponding axis channel will read as a value of -4096 in 2s complement form. To overcome this, simply increase the magnetometer range.

8. References

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9. Appendix

9.1. Legacy hardware: Shimmer2/Shimmer2r

Shimmer2r IMU Daughterboard Configuration

This appendix is written generically and may describe some capabilities that are not present on your board. Please refer to your purchase record or to Figure 9-1, below, to identify which of the following capabilities apply to your device:

1. 3-axis Gyroscope with User Interaction controls
2. 3-axis Magnetic Sensor with User Interaction controls
3. 3-axis Magnetic Sensor and 3-axis Gyroscope with User Interaction controls

All of the configurations extend the capabilities of the *Shimmer* platform. Note that Figure 9-1 and the notes in this section refer to current production hardware only, i.e. SR16-6 or later. For older hardware, please refer to Section 9.2 *Legacy Hardware: Shimmer IMU daughterboards*. See the marking on the board for hardware revision number (SR16-x or SR2-x).

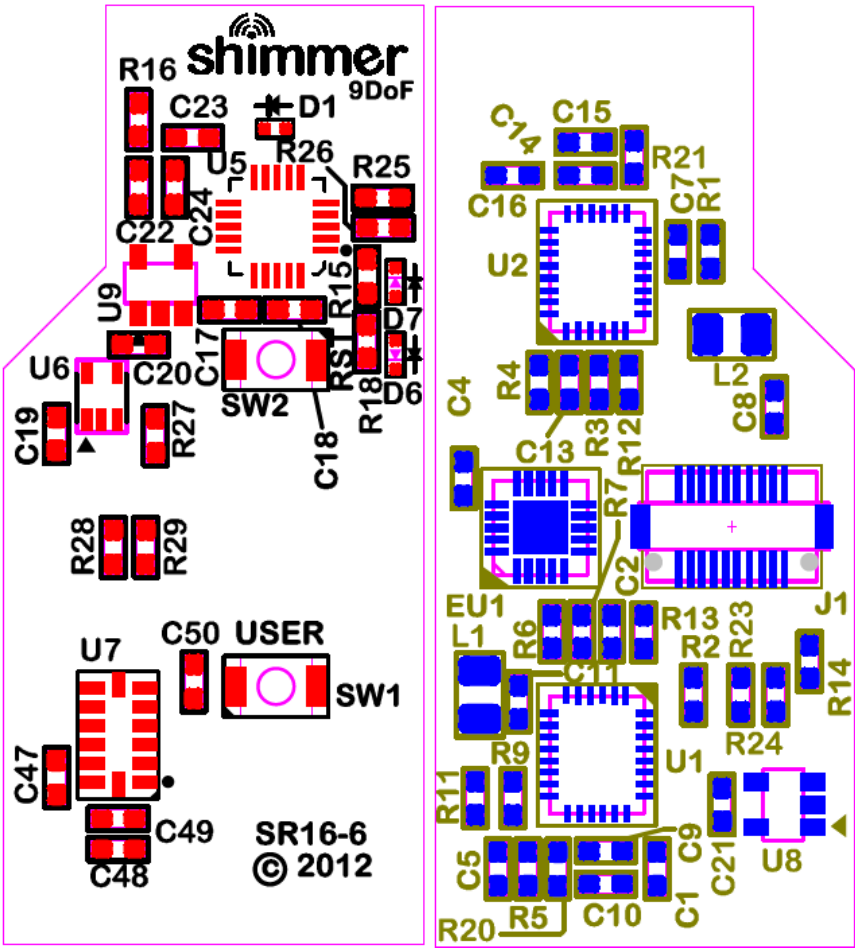


Figure 9-1: Board layout

If the locations marked U1 and U2 are empty, then there is no gyroscope capability on your device.

If the location marked U5 is empty, then there is no magnetometer capability on your device.

Accelerometer

The output of the accelerometer device on the *Shimmer2* and *Shimmer2r* baseboards is analog. An MMA7361 device from Freescale is used. The following approximate values apply to this device:

- Zero-output: 1.5 V.
- Full scale range: ±1.5 g; ±6.0g.
  - Factory option: ±4.0 g; ±12.0 g.
- Sensitivity: 727 mV/g (±1.5 g); 187 mV/g (±6.0 g).

Note that the above specifications are derived from the datasheet for the MMA7361, which assumes a supply voltage of 3.3V, by scaling the values appropriately for *Shimmer2/2r*, on which the MMA7361 is running from a supply voltage of 3V.

Please refer to the manufacturer's datasheets for detailed information.

Magnetometer

A highly integrated MEMs sensor provides 3-axis magnetic field sensing capabilities (digital compassing) on the *Shimmer 9DoF IMU* daughterboard. A HMC5883L[5] device from Honeywell is used. The Shimmer's I2C interface is used to configure and communicate with the sensor. The key features are listed below:

- Resolution: 2 mGa.
- Full Scale Measurement range: selectable up to ±8 Ga measurement range.
- Digital interface supports .75-75 Hz Output Data Rate (ODR).
- Power consumption increases rapidly above the default ODR setting (15Hz).
- Software interface for gain/rate selection, bias, and power control.
- Dedicated micro-power regulator for lowest power User Interface.

Please refer to the manufacturer's datasheets for detailed information.

Gyroscope

The output of the Gyro MEMs devices on the *Shimmer 9DoF IMU* daughterboard and *Shimmer Gyro IMU* daughterboard is analog. Both boards have a fixed reference output and run off of a secondary LDO for improved power-supply noise rejection. LPR450AL and LPY450AL devices from ST Micro are used[6]. The following approximate values apply to these devices:

- Zero-output: 1.5 V [7].
- Sensitivity: 2 mV/(deg/sec).
- Full scale range: ± 500 deg/sec.
  - Factory option: 2000 deg/sec

Please refer to the manufacturer's datasheets for detailed information.

Gain selection

With reference to Figure 9-1, the following parts indicate the full scale range for your board:

- Factory default: (500deg/sec)
  - R6, R9, R12 installed.
  - R7, R11, R3 not installed.
- Customised option: (2000deg/sec)
  - R6, R9, R12 not installed.
  - R7, R11, R3 installed.

---

[5] Note that for legacy hardware, a HMC5843 device from Honeywell was used. See Section 9.2 for details.
[6] Note that for legacy hardware, IDG-500 and ISZ-500 devices from Invensense were used. See Section 9.2 for details.
[7] Note that for legacy hardware, gyro zero-output was 1.35 V. See Section 9.2 for details.

Gyro Input Multiplexer

An analog multiplexer (MUX) provides additional signals for applications based on the logic signal SEL_A0:

Shimmer Signal	**Gyro Input Mode, SEL_A0 = 0**	**Aux-input Mode, SEL_A0 = 1**
ADC6	Y Rotation	X/Y Gyro Zero-voltage VREF
ADC1	X Rotation	X/Y Gyro Zero-voltage VREF[8]
ADC2	Z Rotation	Z Gyro Zero-voltage VREF

Table 2 : Gyro board multiplexer settings

User Interface

The top-side components on the *Shimmer 9DoF IMU* and *Shimmer Gyro IMU* daughterboards provide two switches and an LED indicator.

- Switch, SW1, is application specific; it is pulled high. Its function can be changed by moving resistors as follows:
  - Factory setting: SW1 is user pushbutton (wired to USER_PB/SER0_RTS).
    - R24 installed.
    - R14 installed.
    - R23 not installed.
    - Functionality is SW defined, eg. start-stop control in logging FW.
  - Optional setting: SW1 is reset/power.
    - R23 installed.
    - R24 not installed.
    - R14 not installed.
    - This configuration can be used when easy user power on/off is desired.
  - Notes:
    - R23, R24 are zero-ohm SMT0603 jumpers.
    - R14 is a 100k SMT resistor.
- Switch, SW2, is always tied to Shimmer baseboard reset and can be used to reset/power on/off a *Shimmer2/Shimmer2r*.
- The indicator, D1, is active low and tied to USER_LED/SER0_RXD on the Shimmer baseboard.

The LED should not be confused with the coloured indicators on the Shimmer baseboard (which are exercised by the sample program blink).

Possible uses for the UI components on the board, in a logging or streaming application, are:

- Reset Button press: Restart application.

[8] Note that for SEL_A0 = 1 in legacy hardware, ADC1 was connected to Gyro temperature. See Section 9.2 for details.

- User Button press: Start/Stop logging or data transmission.
- LED: On when logging or streaming data.

Noise Specifications

Table 3 shows the noise performance that can be expected at varying signal bandwidths for the accelerometer on a *Shimmer2r* unit and the gyroscope and magnetometer on an SR16-6 daughterboard (illustrated in Figure 9-1). The sampling rate in each case was 500 Hz and a low-pass filter was used to vary the bandwidth.

Bandwidth (Hz)	50	100	250
Accelerometer RMS noise (m/s^2)	24.2×10^{-3}	36.8×10^{-3}	60.9×10^{-3}
Gyroscope RMS noise (deg/s)	0.185	0.297	0.480
Magnetometer RMS noise (normalised local flux)	0.0123	0.0138	0.0139

Table 3 : Measured RMS noise for Shimmer2r with SR16-6 daughterboard[9]

Expansion Connector Pin-Out for Shimmer2 and Shimmer2r

SHIMMER Net name	SHIMMER Pin Number	Expansion Pin Number	Expansion Function
PV	1	20	PV Supply
GND	2	19	GND
SER0_RTS	3	18	USER_PB
VSENSE_ADC6	4	17	ADC6 (Y-axis Rotation or XY VREF)
VSENSE_ADC2	5	16	ADC2 (X-axis Rotation or XY VREF)
VSENSE_ADC1	6	15	ADC1 (Z -axis Rotation or Z VREF)
BSL_TX	7	14	GYRO_PWREN_N (Low = Enabled)
SER0_CTS	8	13	SEL_A0 (MUX) (Low=Gyro; High= Aux)
GPIO_INTERNAL	9	12	No Connect
BSL_RX	10	11	No Connect
PV_CHG	11	10	No Connect
SER0_RXD	12	9	USER_LED
SER0_TXD	13	8	GYRO ZERO (Gyro HPF RESET) (Low = normal operation; High = reset external high-pass filter)

[9] Measured on recent production units, contact support for additional information.

SPI0_SCLK_EXP	14	7	I2C SCL line for Magnetic sensor
JTAG_MSP_TCK	15	6	No Connect
MSP_RESET_N	16	5	Reset Button
SPI0_SOMI	17	4	No Connect
SPI0_SIMO	18	3	I2C SDA line for Magnetic Sensor
GND	19	2	GND
	20	1	No Connect

Table 4: Expansion Connector Pin-Out

Firmware

Developers should leverage the driver and test application code in the TinyOS and Shimmer github repositories for *Shimmer2r*. The *Shimmer User Manual* also includes tutorial information in the embedded firmware section.

The I2C interface used for magnetic sensing is on USART0, a shared resource with the microSD card on *Shimmer*, *Shimmer2* and *Shimmer2r* platforms. There are non-trivial timing constraints when use of both peripherals is desired.

Gyro reference applications use an abstraction to configure Shimmer to sample 3 channels of Gyro data:

call shimmerAnalogSetup.addGyroInputs();

If the Gyro is installed, the three ADC signals from the GyroMux board are analog outputs from the board that can't be disabled. Applications that do not directly configure the Gyro board (e.g. Blink, JustFATLogging, Null) should include the following lines:

TOSH_MAKE_ADC_1_INPUT();

TOSH_MAKE_ADC_2_INPUT();

TOSH_MAKE_ADC_6_INPUT();

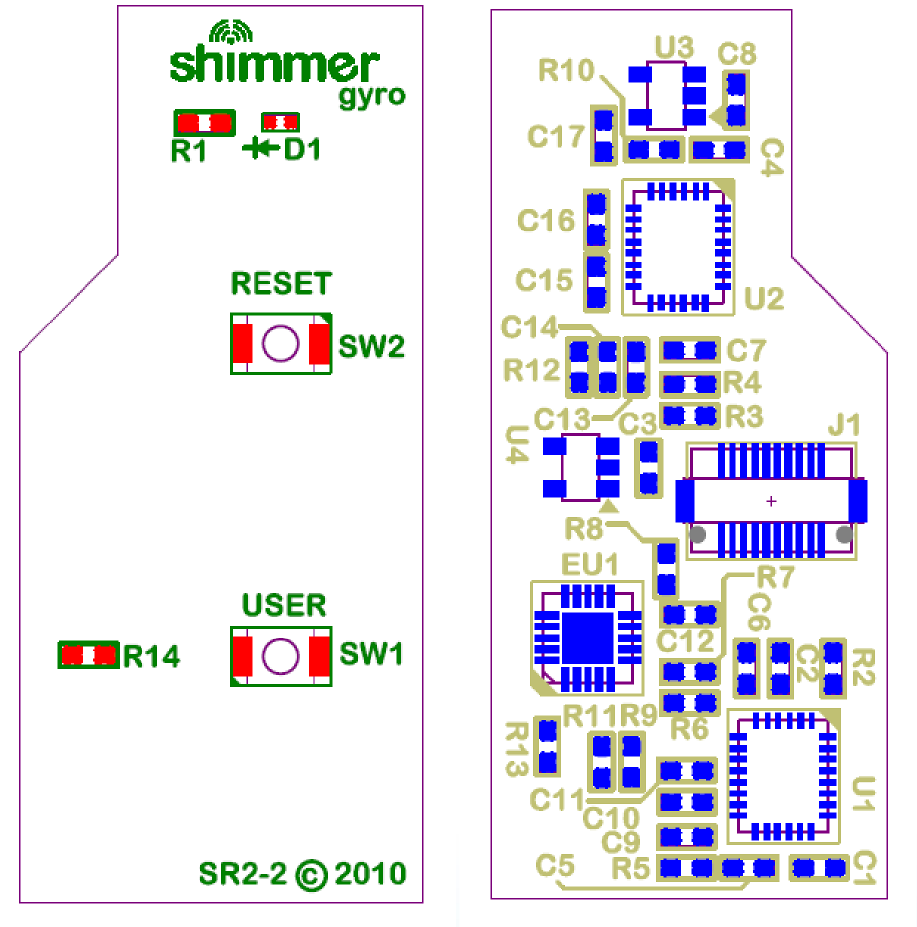
If the user button is installed, it is connected to SER0_RTS with a weak pull-up resistor on the *Shimmer 9DoF IMU* and *Shimmer Gyro IMU* daughterboards. When depressed, the signal is grounded. This pin should be defined as an input in deployments where the button is user accessible to avoid brownouts or increased power consumption.

TOSH_MAKE_SER0_RTS_INPUT();

9.2. Legacy Hardware: Shimmer IMU daughterboards

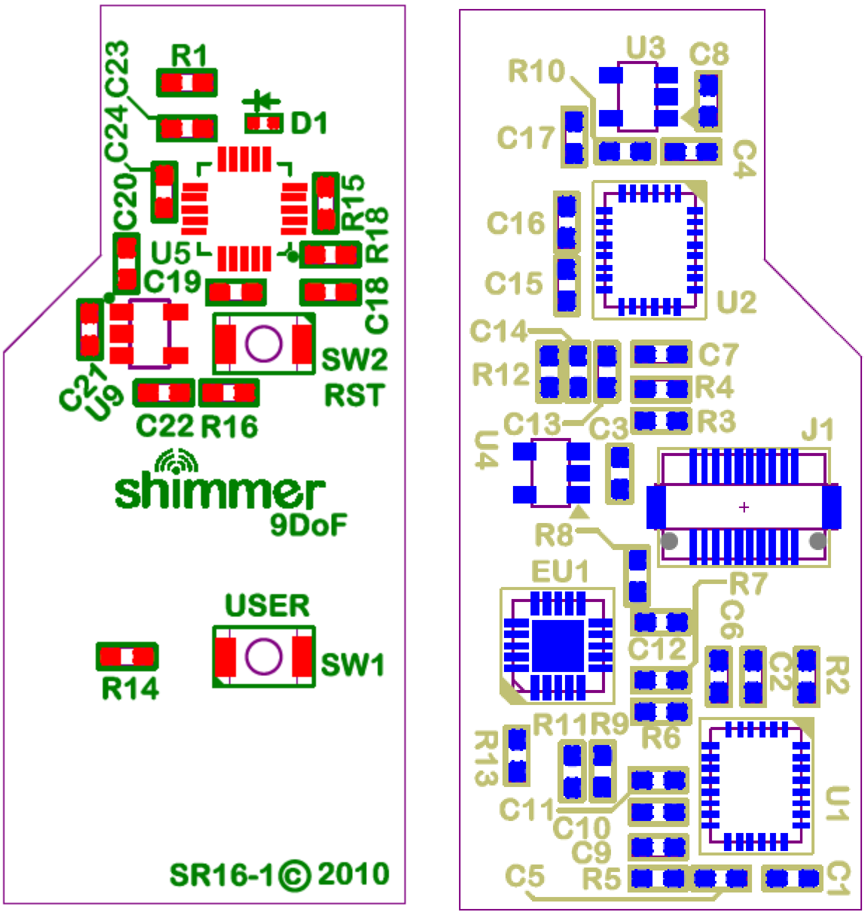
Previous hardware revisions of *Shimmer 9DoF IMU* daughterboards (SR16-1, SR16-2, SR16-3, SR16-4, SR16-5) and *Shimmer Gyro IMU* daughterboards (SR2-1, SR2-2, SR2-3) used a HMC5843 magnetometer device from Honeywell and IDG-500 and ISZ-500 MEMs gyroscope devices from Invensense, with hardware configurable gyroscope signal range and optional user interaction controls. The following information is provided as legacy support for these devices.

Component locations for boards without magnetic sensing



- If the locations marked U1 and U2 are empty, there is no gyro capability on your device.
- If the location marked SW1 is empty, there is no user interaction control on your device.
- For 500°/sec gyro: R3,R7 and R11 are populated and R6,R9 and R12 are not.
- For 110°/sec gyro: R6,R9 and R12 are populated and R3,R7 and R11 are not.

Component locations for boards with magnetic sensing



- If the locations marked U1 and U2 are empty, there is no Gyro capability on your device.
- If the location marked SW1 is empty, there is no user interaction control on your device.
- For 500°/sec gyro: R3,R7 and R11 are populated and R6,R9 and R12 are not.
- For 110°/sec gyro: R6,R9 and R12 are populated and R3,R7 and R11 are not.

Magnetometer Specifications

- Resolution: 7 mGa.
- Full Scale Measurement range: selectable up to ±4.5 Ga measurement range.
- Digital interface supports .5-50 Hz Output Data Rate (ODR).
- Power consumption increases rapidly above the default ODR setting (10Hz).
- Software interface for gain/rate selection, bias, and power control.
- Dedicated micro-power regulator for lowest power consumption.

Please refer to the manufacturer's datasheets for detailed information.

Gyro Signal Range

The output of the Gyro MEMs devices is analog. The *Shimmer 9DoF IMU* daughterboard has a fixed reference output and runs off of a secondary LDO for improved power-supply noise rejection. Zero-output will be approximately 1.35V vs. 1.50V on the *Shimmer Gyro IMU* daughterboard. In 500°/sec mode, the sensitivity is 2mV/°/sec. In 110°/sec that value is 9.1 mv/°/sec. In both cases, the full scale range is .35V-2.35V, well within the range of the Shimmer's ADC. IDG-500 and ISZ-500 MEMs devices from Invensense are used. Please refer to the manufacturer's datasheets for detailed information.

Gyro Calibration

The board has an auto-zero feature for use in the more sensitive 110°/sec configuration. While the gyro is stationary, a 20-500µS pulse on the Gyro_Zero signal will initiate the auto-zero function and null any zero-rate offset.

Gyro Input Mux

An analog multiplexer provides additional signals for applications based on the logic signal SEL_A0:

Shimmer Signal	Gyro Input Mode, SEL_A0 = 0	Aux-input Mode, SEL_A0 = 1
ADC6	Y Rotation	X/Y Gyro Zero-voltage VREF
ADC1	X Rotation	X/Y Gyro Temperature Sense
ADC2	Z Rotation	Z Gyro Zero-voltage VREF

The temperature sensor has a 1.25V offset at room temperature and a 4mV per degree C sensitivity. For precision measurements, the zero-offset should be calibrated against an external thermometer.

Other component Options

- C3 is a high-frequency shunt on the temperature sensor (output impedance is 12k).
- R8 and C12 provide additional filtering on a buffered version of the signal (R8 = 10 ohms, C12 is .1µF)
- C2,C5,C13 are filtering external capacitors for the high-sensitivity mode of the gyro. For more information see the IDG-500 Datasheet at www.invensense.com

9.3. Legacy sensor axis directions

The *Shimmer2* or *Shimmer2r* is equipped with three single-axis accelerometers, such that its reference axes are arranged as in Figure 9-2; the figure shows the axes relative to two of the available *Shimmer2*/*Shimmer2r* enclosures so that it can easily be matched up to any device.

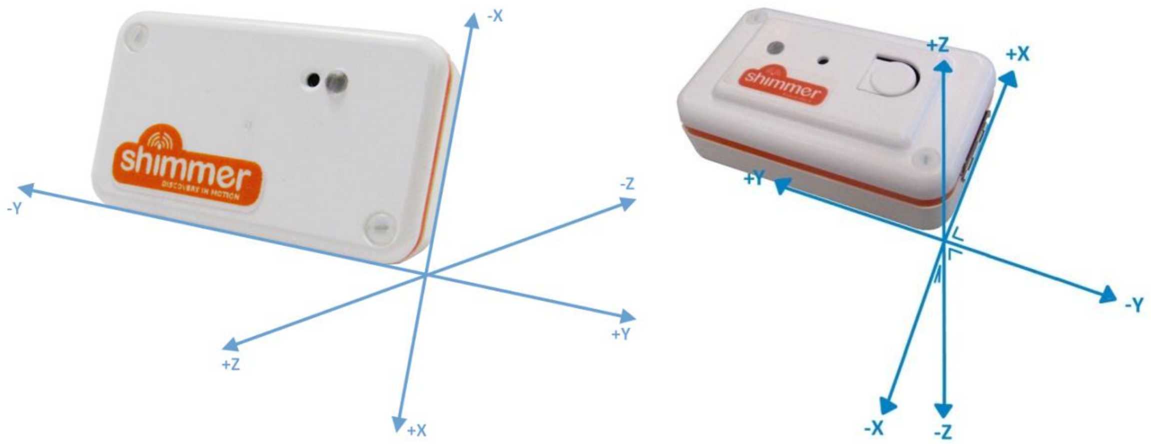


Figure 9-2: Shimmer accelerometer axis directions - Shimmer baseboard only enclosure (left) and Shimmer IMU enclosure (right)

9.4. Errata and Updates

The accelerometer RMS noise values quoted in Table 6.2 of v1.0 of this User Guide were erroneously labelled as having units of m/s^2, when, in fact, the numerical values were in units of *g* (the gravitational constant ≈ 9.81 m/s^2). This has been corrected in the current document and the numerical values are now quoted in m/s^2.

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