Know Your Sensors:
An Introduction to Inertial Sensors

Eran Belaish, CMO

Whitepaper

An IMU provides 3D orientation estimation by fusing data from different inertial sensors:

- Accelerometer force/acceleration measurement
- Gyroscope angular rate measurement
- Magnetometer magnetic field measurement

Inertial Sensing Technology

There comes a time when your product needs to include inertial sensors. At that point, you might have no previous experience with this technology. In other cases, you might have less mileage with some sensors than others. Whatever the case, this whitepaper provides practical knowledge that will give you a head start covering three popular sensors:

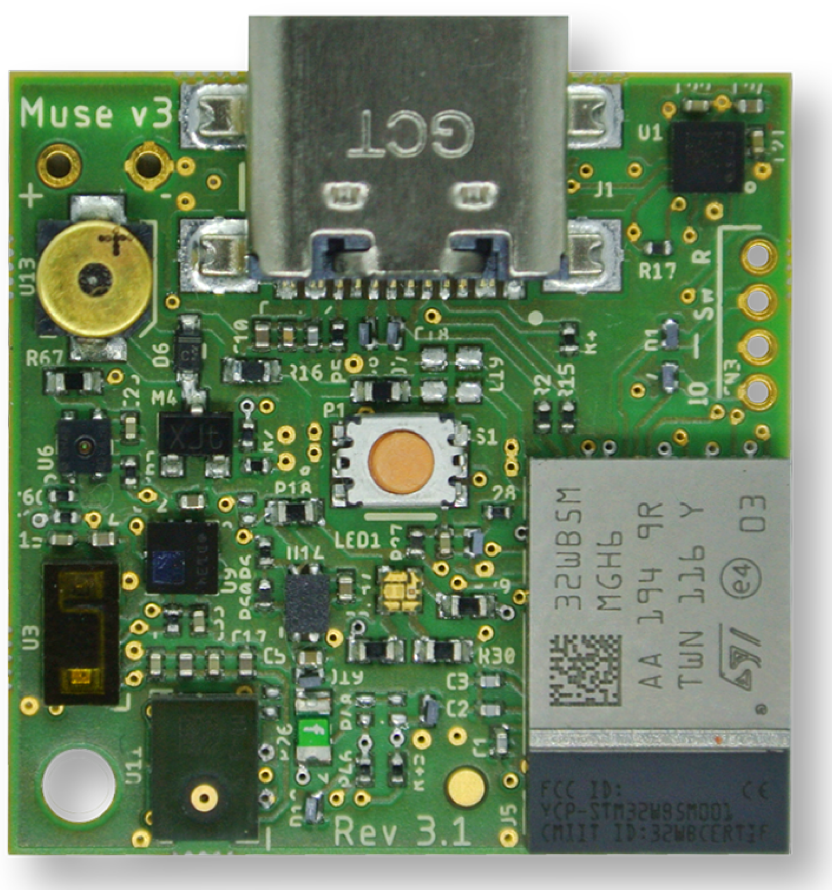
- Accelerometer – force and acceleration measurement
- Gyroscope – angular rate measurement
- Magnetometer – magnetic field measurement

Each one of these can work as a standalone sensor. Often though, the readings of at least two of them are combined using a technique called sensor fusion. While this paper covers each sensor individually, you can learn more about sensor fusion here.

IMU and AHRS

An Inertial Measurement Unit (IMU) is a device that typically integrates a gyroscope and an accelerometer to measure angular rates and accelerations. This combination of sensors is also known as 6-axis or 6DoF.

An Attitude and Heading Reference System (AHRS) is an IMU that integrates a magnetometer and sensor fusion algorithms to determine 3D orientation.
This combination of sensors is also known as 9-axis or 9DoF.



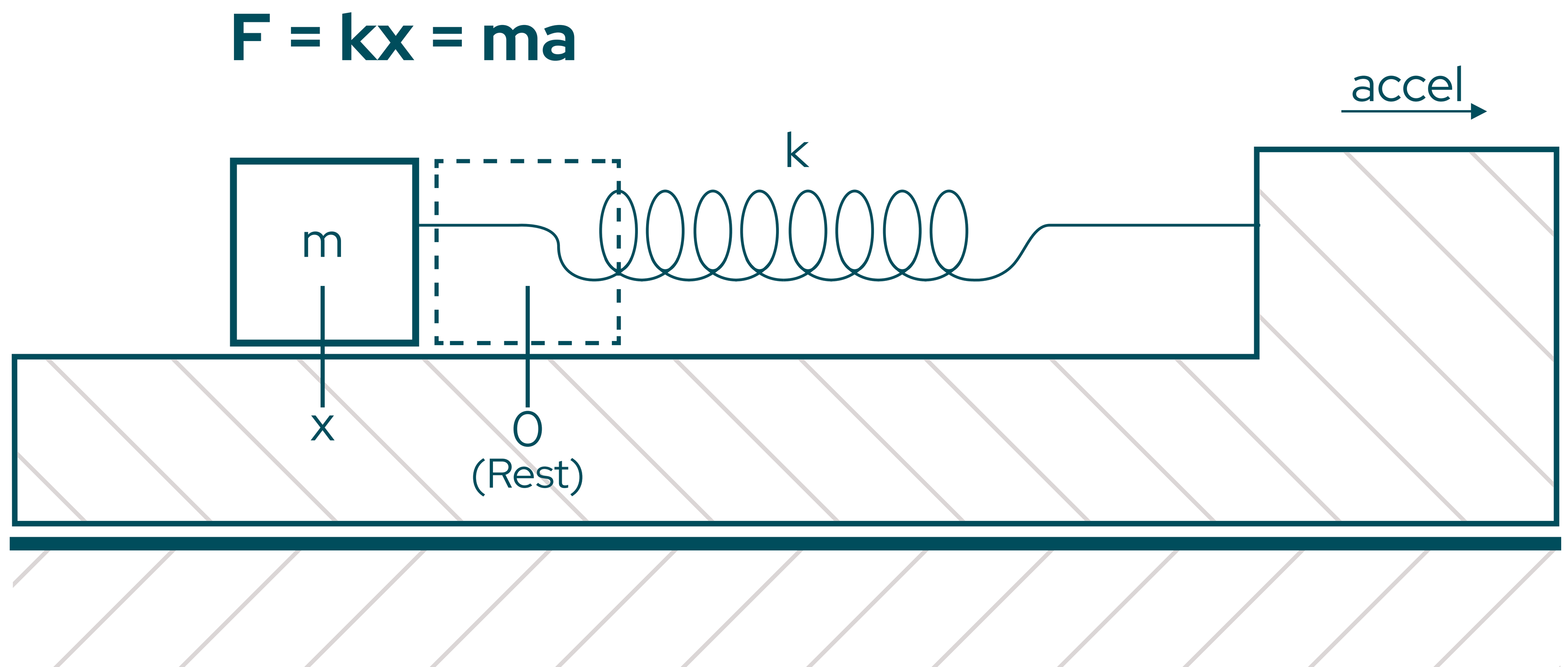
These devices have become a fundamental part of a broad range of consumer, industrial and automotive applications. You can see an example of such a multi-sensor system here. While such systems include multiple sensors, you also need to be familiar with the discrete components detailed below.

Accelerometer

Accelerometers are based on a mass-spring system.
By measuring the displacement x of a mass m attached to a spring constant k, they can determine the acceleration a=kx/m.

Accelerometers measure the change in velocity over time, also known as inertial acceleration. They sense the linear acceleration of the object they're attached to in the form of movement, shock or vibration. Typical accelerometer readings are in units of g, where one g is about 9.81 m/s^2.

There are several types of accelerometers: mechanical, quarts and MEMS. All of them rely on the same principle of a spring-mass system. In such a system, the mass can move along a fixed direction known as the sensitivity axis. When the mass (**m** below) is subjected to linear acceleration along the sensitivity axis, it shifts from its resting position. According to Hooke's law of elasticity, this displacement (**x** below) is proportional to the pulling force (**F** below). The spring constant (**k** below) denotes the proportionality between displacement, x, and force, F, and all in all, we get F=kx.



A mass-spring system

Another physical principle that comes into play here is Newton's second law of motion **F=ma**, where ***a*** is the acceleration of the mass ***m***. Combining Hooke's and Newton's laws produces F=kx=ma, which leads to **a=kx/m**. With ***k*** and ***m*** being constant, by knowing the displacement ***x*** you can easily calculate the acceleration.

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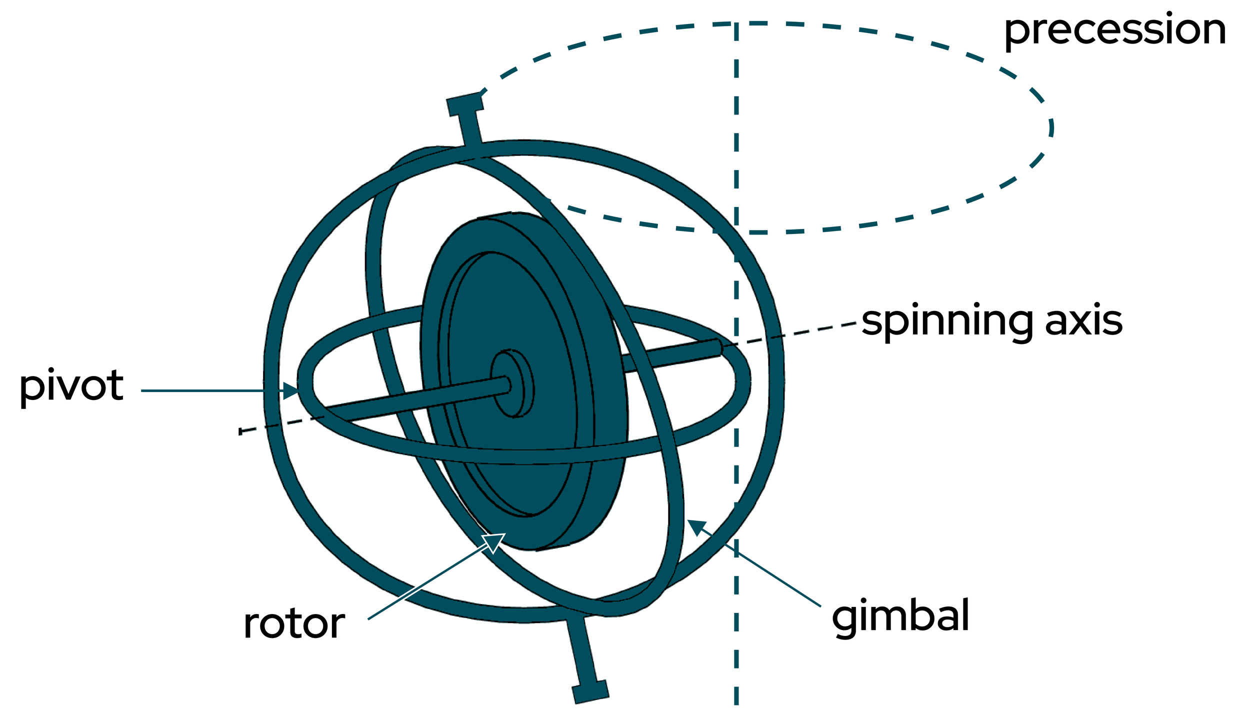
The sense-mode displacement is a direct measure of the applied angular rate.

Gyroscope

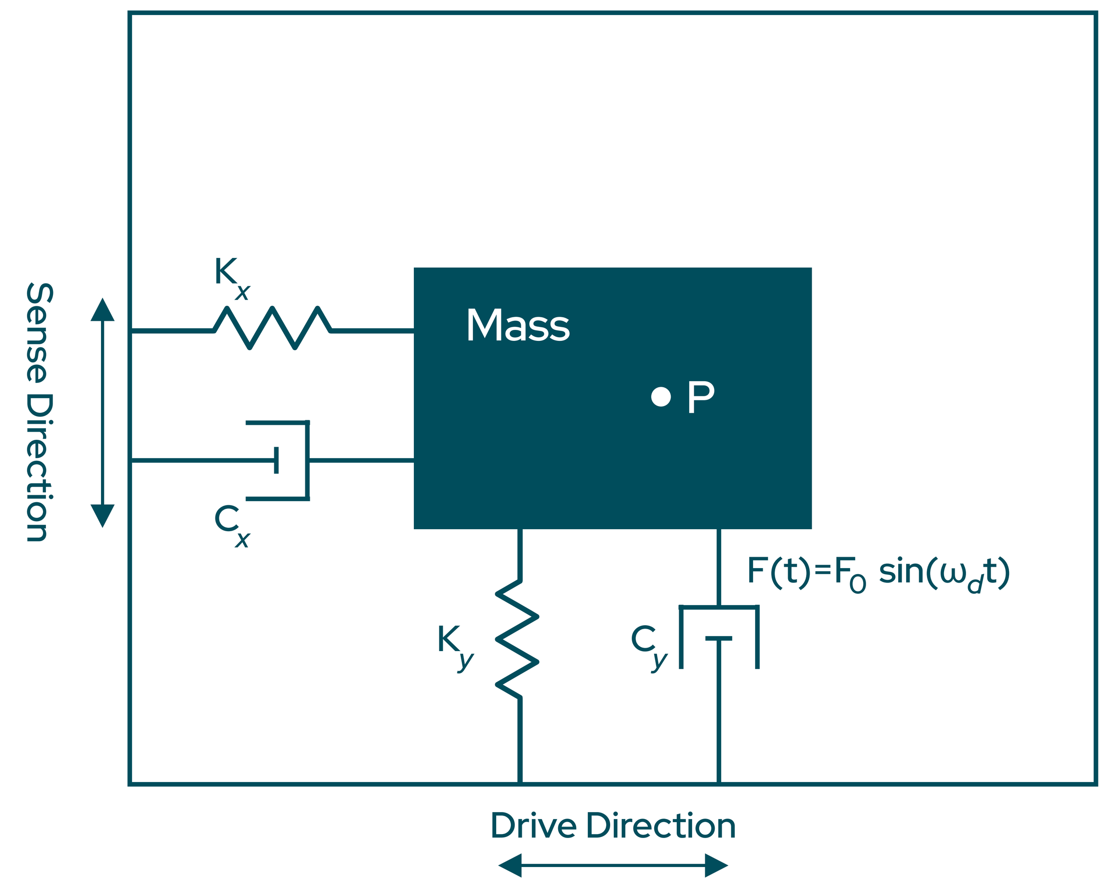
A Gyroscope relies on the Coriolis effect to measure the angular velocity of an object in units of degrees per second (dps) or revolutions per second (rps). It consists of a **rotor** mounted on a spinning axis in the center of a second larger wheel called a **pivot**. The pivot allows the rotation of the rotor on a particular axis called a **gimbal**. When the rotor spins, the gyroscope points continuously in the same direction.



A mechanical gyroscope

In the sensor market, you can find mechanical, fiber-optic, ring laser, quarts and MEMS gyroscopes, each with different performance levels.

MEMS gyroscopes use a vibrating electro-mechanical element instead of the rotating parts above, allowing far greater miniaturization. They are based on the energy transfer between two orthogonal vibration modes, **drive mode** and **sense mode**. The two modes are coupled by the dynamics of the Coriolis force, which is proportional to the angular velocity.



A vibratory MEMS gyroscope

A MEMS Gyroscope can be modeled as a **harmonic oscillator** with two degrees of freedom: drive mode and sense mode. The sense-mode displacement is a direct measure of the applied angular rate. It often operates as a closed-loop system to increase the bandwidth and dynamic range of the gyroscope.

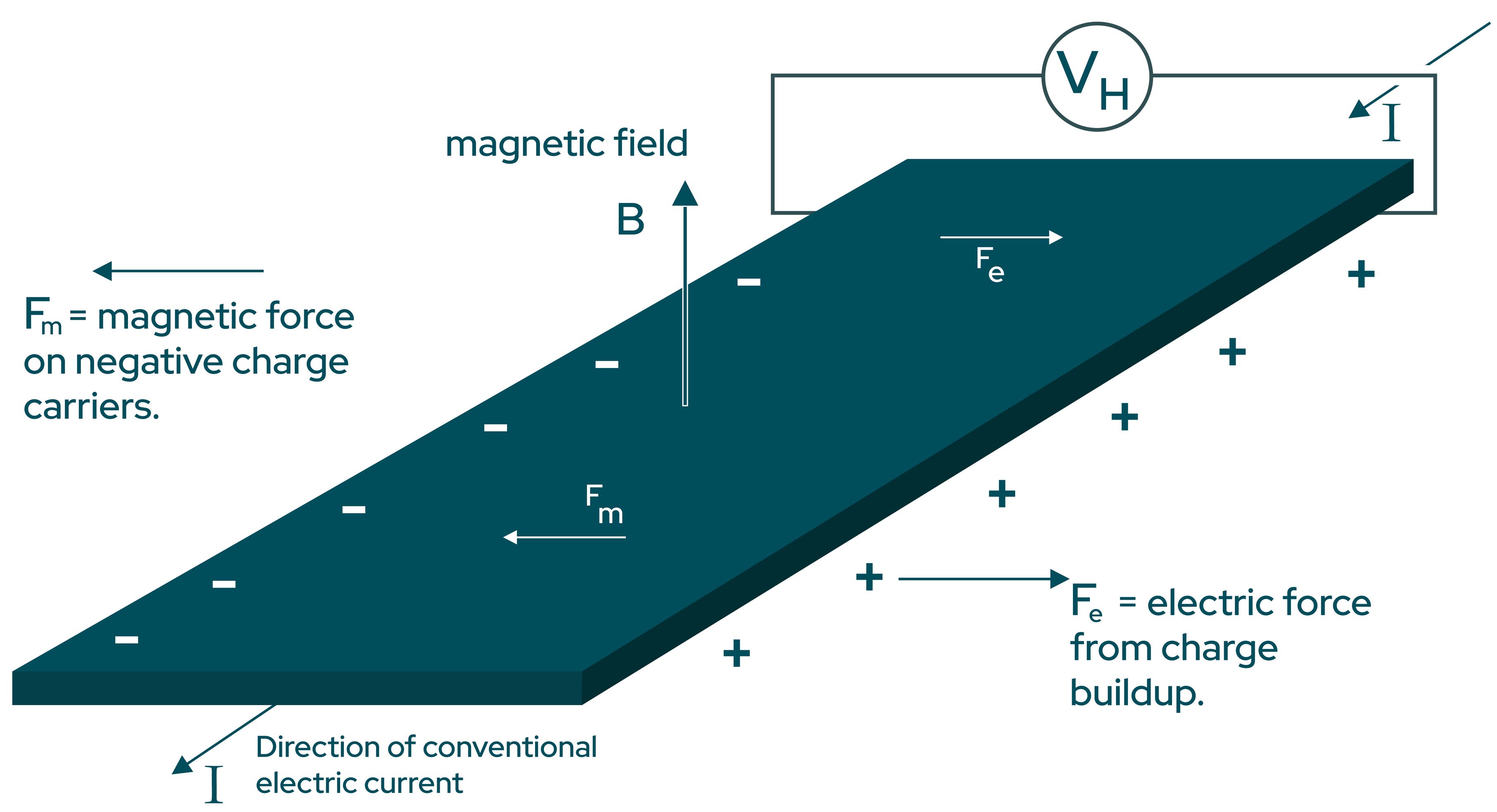
Most magnetometers are based on the Hall effect—setting current through a conductive plate causes the electrons to flow straight from one side of the plate to the other. The measured plate voltage depends on the strength and direction of nearby magnetic fields.

Magnetometer

Magnetometers measure the magnetic field intensity and direction around the instrument in units of *gauss* (G) or *tesla* (T). Being sensitive to magnetic fields, they can detect the direction of the magnetic north for geographic positioning. A variety of magnetometers exist with different physical working principles:

- **Induction magnetometers** that work according to Faraday's law
- **Magnetic magnetometers** are made by the principle that current in the magnetic field can generate a Lorentz force
- **Magneto-resistive magnetometer** where conductor resistivity changes in the magnetic field
- **Magneto-optical magnetometers** based on Faraday's magneto-optical effect
- **Superconducting Quantum Interference Devices** (SQUID) based on the Josephson effect

Almost 90% of the sensors on the market use the Hall effect—setting current through a conductive plate causes the electrons to flow straight from one side of the plate to the other. When there's a magnetic field near the device, it disturbs the flow deflecting electrons and positive poles to opposite sides of the plate. The measured plate voltage (V_H below) depends on the magnetic field strength and direction.



The Hall effect

The other 10% of sensors use the magneto-resistive effect. They contain materials such as Iron (Fe) and Nickel (Ne) that change their resistance under a magnetic field.

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Summary

Accelerometers, gyroscopes, magnetometers—these inertial sensors are everywhere you look. You can mostly find them in IMU hardware processed by sensor fusion software. They rely on different physical principles that determine the capabilities of each one of them:

- **Accelerometer – based on the spring-mass system**
- **Gyroscope – based on a vibrating electro-mechanical system**
- **Magnetometer – based on the Hall effect**

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