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THE FIVE MOTION SENSES: USING MEMS INERTIAL SENSING TO TRANSFORM APPLICATIONS

Though MEMS (microelectromechanical systems) technology has been on the job for about two decades in airbag deployment and automotive pressure sensors, it took the motion-sensing user interfaces featured in the Nintendo® Wii® and the Apple® iPhone® to catapult broad awareness of what inertial sensors can do.

Still, to an extent, the idea persists that inertial sensors are useful mainly when the end product has a need to detect acceleration and deceleration. True enough from a purely scientific view. Yet, that could be to miss out on many of the expanding uses of MEMS accelerometers and gyroscopes in areas such as medical devices, industrial equipment, consumer electronics, and automotive electronics.

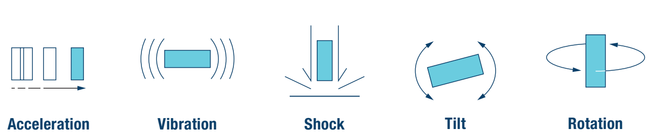
Looking at what becomes possible in each of the five modes of motion sensing vastly expands the options beyond today's high volume MEMS applications. These five modes are acceleration (including translational movement such as position and orientation), vibration, shock, tilt, and rotation.

For instance, an accelerometer with activity detection can enable power management techniques by telling a device to go into the lowest power consumption mode when that device is determined to be inactive in the absence of movement or vibration. Complicated controls and physical buttons are being replaced by gesture-recognition interfaces controlled by the tap of a finger. In other use cases, the operation of end products becomes more precise, such as when a compass has compensation for the tilt angle at which it is held in your hand.

This article offers a sample of the ways that advanced, commercially available MEMS accelerometers and gyroscopes are set to transform an incredibly diverse scope of end products through the five types of motion sensing.

Introduction to Motion Sensing and MEMS

Acceleration, vibration, shock, tilt, and rotation—all except rotation are actually different manifestations of acceleration over different periods of time. However, as humans we don't intuitively relate to these motion senses as variations on acceleration/deceleration. Considering each mode separately helps in envisioning more possibilities.



Acceleration (remember, including translational movement) measures the change in velocity in a unit of time. Velocity is expressed in meters per second (m/s) and includes both the rate of displacement and direction of movement. It follows that acceleration is measured in meters per second squared (m/s^2). Acceleration with a negative value—imagine a car slowing down when the driver applies the brakes—is known as deceleration.

Now consider acceleration over various periods of time. Vibration can be thought of as acceleration and deceleration that happens quickly and in a periodic manner.

Similarly, shock is acceleration that occurs instantaneously. But unlike vibration, a shock is a nonperiodic function that typically happens once.

Let's stretch out the length of time again. When an object is moved to alter its tilt or inclination, some change in position with respect to gravity is involved. That movement tends to happen rather slowly compared with vibration and shock.

Because these first four modes of motion sensing each involve a certain aspect of acceleration, they are measured by *g*-force, the unit of force that gravity exerts on an object on the Earth (one *g* equals 9.8 m/s^2). A MEMS accelerometer detects tilt by measuring the effect the force of gravity exerts on the axes of the accelerometer. In the instance of a 3-axis accelerometer, three separate outputs measure acceleration along the X, Y, and Z axes of motion.

The accelerometers with the largest share of the market today use differential capacitors to measure *g*-force, which is then converted into volts or bits (in the case of digital output accelerometers), and then passed to a microprocessor to perform an action. Recent advances in technology have made it possible to manufacture tiny MEMS accelerometers in low *g* and high *g* sensing ranges with much wider bandwidth than previously, greatly increasing the field of potential applications. A low *g* sensing range is less than 20 *g* and deals with motion a human can generate. High *g* is useful for sensing motion related to machines or vehicles—in essence, motion that humans cannot create.

So far we have discussed only linear rate motion, the type of motion that includes acceleration, vibration, shock, and tilt. Rotation is a measure of angular rate motion. This mode differs from the others because rotation may take place without a change in acceleration. To understand how that works, picture a 3-axis inertial sensor. Say that the sensor's X and Y axes are parallel to the Earth's surface; the Z axis is pointing toward the center of the Earth. In this position, the Z axis measures 1 *g*; the X and Y axes register 0 *g*. Now rotate the sensor to move only about the Z axis. The X and Y planes simply rotate, continuing to measure 0 *g* while the Z axis still measures 1 *g*.

MEMS gyroscopes are used to sense this rotational motion. Because certain end products must measure rotation in addition to other forms of motion, gyroscopes may be integrated in an IMU (inertial measurement unit) that embeds a multiaxis gyroscope and multiaxis accelerometer.

Acceleration in Usability and Power Management

Earlier we observed that acceleration comes into play for detecting movement and position. This creates the possibility of using a MEMS accelerometer to notice when a device is picked up and put down, which when detected can generate an interrupt that powers functions on and off automatically. Various combinations of functions can be kept active or put into the lowest power state possible. Movement-driven on/off features are human-friendly because they eliminate repetitive actions on the user's part. What's more, they enable power management that lets the device go longer between recharging or replacing the battery. An intelligent remote control with a backlit LCD is among the potential scenarios.

Another way to use an accelerometer to sense movement and generate an interrupt would be in a radio for military or public safety personnel. To keep communication secure, when the radio stops being worn or carried, it could require reauthentication before permitting user access. Note that to be practical for a portable or small form factor design, these two preceding use cases would depend on accelerometers that draw little current: several microamps (μA) at most.

Another application for movement sensing is in medical equipment such as automated external defibrillators. Typically, AEDs have been designed to deliver a shock that gets the patient's heart pumping again. When that fails, manual cardiopulmonary resuscitation must be performed. A less experienced rescuer might not compress the patient's chest enough for effective CPR. Accelerometers embedded in the AED's chest pads can be used to give the rescuer feedback on the proper amount of compression by measuring the distance the pad is moved.

Vibration for Monitoring and Energy Saving

Slight changes in vibration serve as a leading indicator of worn bearings, misaligned mechanical components, and other issues in machinery, including industrial equipment. Very small MEMS accelerometers with very wide bandwidth are ideal for monitoring vibration in motors, fans, and compressors. Being able to perform predictive maintenance lets manufacturing companies avoid damage to expensive equipment and prevent breakdowns that cause costly productivity loss.

Measuring changes in the equipment's vibration signature could also be used to detect whether machinery is tuned to operate in an energy-efficient manner. Unless corrected, this inefficient operation could hurt a company's green manufacturing efforts and drive up its electricity bills or eventually lead to damaged equipment.

Shock, Gesture Recognition, and More

The disk drive protection found in many notebook PCs is among the most widely implemented applications of shock sensing to date. An accelerometer detects tiny *g*-forces that indicate the notebook is falling or dropping, which is a precursor to a shock event: hitting the floor. Within milliseconds, the system orders the hard disk drive head to be parked. Parking the head stops contact with the disk platter during impact, preventing damage to the drive and the resulting data loss.

Gesture recognition interfaces are a promising new use for this type of inertial sensing. Defined gestures, such as taps, double-taps, or shakes, allow users to activate different features or adjust the mode of operation. Gesture recognition makes devices more usable where physical buttons and switches would be difficult to manipulate. Button-free designs can also reduce overall system cost, in addition to improving the durability of end products such as underwater cameras, where the opening surrounding a button would let water seep into the camera body.

Small form factor consumer electronics products are only one application area in which accelerometer driven gesture recognition is finding a place. Thanks to extremely small, low power MEMS accelerometers, tap interfaces can be a good fit for wearable and implantable medical devices such as medication delivery pumps and hearing aids.

Tilt Sensing for Precision Operation

Tilt sensing has tremendous potential in gesture recognition interfaces as well. For instance, one-handed operation may be preferable in applications such as construction or industrial inspection equipment. The hand not operating the device remains free to control the bucket or platform where the operator stands, or perhaps to hold a tether for safety's sake. The operator could simply "rotate" the probe or device to adjust its settings.

A 3-axis accelerometer would sense the rotation as tilt in this case: measuring low speed changes in inclination in the presence of gravity, detecting the change in the gravity vector, and determining whether the direction is clockwise or counterclockwise. Tilt detection could also be combined with tap (shock) recognition to let the operator control more functions of the device single-handedly.

Compensating for the position of a device is another significant area where tilt measurement is useful. Take the electronic compass in a GPS (global positioning system) or mobile handset. A well-known problem here is the heading error that results when the compass is not positioned exactly parallel to the surface of the Earth.

Industrial weigh scales are another example. In this application, the tilt of a loaded bucket relative to the Earth must be calculated to read the weight accurately. Pressure sensors, such as those used in automobiles and industrial machinery, are likewise subject to gravity's effects. These sensors contain diaphragms whose deflection changes depending upon the position in which the sensor is mounted. In all these situations, MEMS accelerometers perform the necessary tilt sensing to compensate for the error.

Rotation: Gyroscopes and IMUs in Action

As already noted, real-world applications of MEMS technology can benefit when rotation is combined with other forms of inertial sensing. In practice this calls for using an accelerometer, as well as a gyroscope.

Inertial measurement units have been introduced that include a multiaxis accelerometer, a multiaxis gyroscope, and—to increase heading accuracy further—a multiaxis magnetometer. The IMU may, in addition, provide a full 6 degrees of freedom (6DoF). This brings ultrafine resolution to applications such as medical imaging equipment, surgical instrumentation, advanced prosthetics, and automated guidance for industrial vehicles. Besides highly precise operation, another advantage of selecting an IMU is that its multiple functions can be pretested and precalibrated by the sensor's manufacturer.

IMUs are also proving useful in cases where the requirement for precision might not be as obvious. Among the examples is an intelligent golf club that tracks and records every movement of a swing so that the golfer's technique can be refined. Accelerometers inside the club measure the acceleration and swing plane, while gyroscopes measure pronation, or the twist of the golfer's hands, during the swing. The golf club records the data collected during play or practice for later analysis on a PC.

New Wave of Signal Processing

Whether the need is for user-friendly features, minimizing power consumption, eliminating physical buttons and controls, compensating for gravity and position, or more intelligent operation, MEMS-based inertial sensing offers an abundance of options to explore across all five motion senses.

Innovators such as Analog Devices, with its *i*MEMS® Motion Signal Processing™ portfolio, lead in creating the accelerometers and gyroscopes needed to deliver this next wave of signal processing. An expanding scope of motion sensing applications will benefit from the small size, high resolution, low power consumption, high reliability, signal conditioning circuitry, and integrated functionality that these IC solutions provide.

References

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Analog Devices, Inc.
Worldwide Headquarters

Analog Devices, Inc.
One Technology Way
P.O. Box 9106
Norwood, MA 02062-9106
U.S.A.
Tel: 781.329.4700
(800.262.5643, U.S.A. only)
Fax: 781.461.3113

Analog Devices, Inc.
Europe Headquarters

Analog Devices GmbH
Otl-Aicher-Str. 60-64
80807 München
Germany
Tel: 49.89.76903.0
Fax: 49.89.76903.157

Analog Devices, Inc.
Japan Headquarters

Analog Devices, KK
New Pier Takeshiba
South Tower Building
1-16-1 Kaigan, Minato-ku,
Tokyo, 105-6891
Japan
Tel: 813.5402.8200
Fax: 813.5402.1064

Analog Devices, Inc.
Asia Pacific Headquarters

Analog Devices
5F, Sandhill Plaza
2290 Zuchongzhi Road
Zhangjiang Hi-Tech Park
Pudong New District
Shanghai, China 201203
Tel: 86.21.2320.8000
Fax: 86.21.2320.8222

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