PCB Design Guidelines for InvenSense MotionTracking™ Devices

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1. Revision History

Revision Date	Revision	Description
Dec. 18, 2012	1.0	Initial Release

2. Introduction

This document provides high-level placement and layout guidelines for InvenSense MotionTracking™ devices, which may incorporate a combination of gyroscope, accelerometer, and magnetometer sensors. Each sensor has specific requirements in order to ensure the highest performance in a finished product. For a layout assessment of your design, including placement and estimated magnetic disturbances, please contact InvenSense.

3. General Description of InvenSense MotionTracking Devices

InvenSense MotionTracking Devices, such as the MPU-6050, MPU-6500, MPU-9150, or MPU-9250 consist of combinations of 3-axis MEMS gyroscopes, 3-axis MEMS accelerometers, and 3-axis magnetometers as well as a Digital Motion Processor™ (DMP™) hardware accelerator engine.

4. Compass Design Guidelines

4.1 Magnetic Distortion

Distortions in the magnetic field are often observed within electronic devices and affect the angle accuracy of magnetic data. There are two basic types of magnetic field distortion.

Hard Iron Distortion: This is a scaling of the sensed magnetic field, caused by magnetized or rare earth magnetic materials. Since the magnetic field is constant, it can be compensated for by subtracting the additive field, as long as the field does not cause the compass to saturate. Common devices which cause Hard Iron distortion include speakers, motors, and auto-focus actuators. Fig. 4.1 shows the change in sensed magnetic field from a 30 µT field caused by Hard Iron distortion.

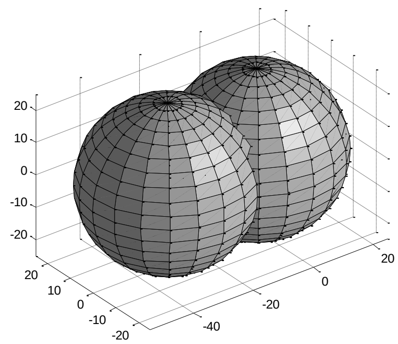


Figure 4.1: Change in magnetic field caused by Hard Iron distortion

Soft Iron Distortion: This is the result of the magnetic field bending around materials which interact with a magnetic field. When placed near a sensor, the material may bend, or attenuate the field causing a reduction in sensitivity or angular accuracy of the magnetometer. Common sources of soft iron distortion include iron, cobalt, nickel, and their alloys, ferritic and martensitic stainless steels (SUS400, SUS 6000, etc.). These materials may be used in a wide variety of common components, including heat sinks, fasteners, hinges, connectors, batteries, spring steel dome switches, chip capacitors, and some integrated circuits. Fig. 4.2 shows the change in sensed magnetic field caused by Soft Iron distortion, which has the effect of transforming the typically spherical sensed field into an ellipsoid.

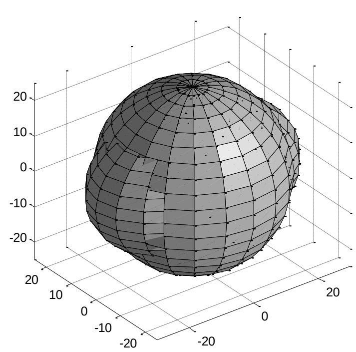


Figure 4.2: Change in magnetic field caused by Soft Iron distortion

Ferritic, Martensitic (400 series), and work-hardened Austenitic (300 series) stainless steels are "soft iron" materials, and can affect the sensed magnetic field. Stainless steels which may not have a significant interaction with magnetic fields in their annealed state, may exhibit an increased interaction when cold-worked. This may occur during a stamping, forming, or bending process which commonly occurs. Therefore, it is important to evaluate both the mechanical process, or to examine completed parts, as well as the material to be used.

Materials which have no (or only very weak) interaction with magnetic fields include copper, aluminum, plastic, magnesium, brass (Cu + Zn), SUS305, titanium, gold, silver, and some stainless steels.

In discussion, the term “Hard Iron” commonly refers to a rare earth magnetic material, which has a permanent magnetism. Similarly, “Soft Iron” commonly refers to an iron (Fe) containing substance that may be magnetized. It is important to note that both *Hard Iron Distortion* and *Soft Iron Distortion* may be exhibited by either material to varying degrees.

Magnetic fields decay quickly with distance. Typically, the best resolution to either hard or soft iron distortion will be achieved when locating the compass as far away from sources of distortion as is practical, and/or substituting alternatives to “soft iron” materials in the product. It is recommended to keep the magnetometer at least 10mm away from permanently magnetized materials in order to reduce the likelihood of device saturation. Figure 4.3 provides an example of magnetometer location with respect to sources of hard and soft iron distortion in a finished product.

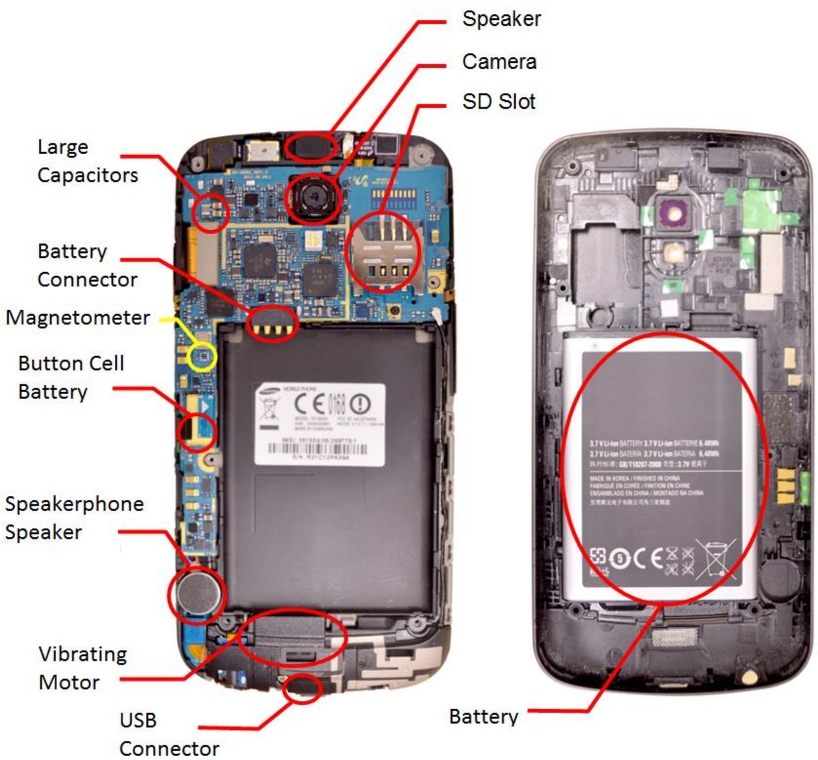


Figure 4.3: Typical handset components causing hard/soft iron effects and magnetometer location

Care should be taken in order to avoid introducing soft or hard iron effects to the magnetometer based on current device configuration. Folding or rotating devices such as clamshell phones, dual-screen tablets, laptops, convertible notebooks; or critical accessories, such as smart cases, port adapters, docking stations, should be analyzed for magnetic interference for all possible orientations of the device. Magnetic or “soft iron" materials should not be placed near the magnetometer when the device in any configuration as it will invalidate the current calibration and require an immediate recalibration for best performance.

4.2 Calibration of Hard and Soft Iron Distortion

Hard iron distortion can be corrected through a sensor bias estimation. The bias introduced by hard iron distortion may be calculated by measuring the magnetometer at known orientations and estimating a fixed offset, or applying a spherical model to magnetometer data and computing the center of magnetic sphere.

Compensation of soft iron distortion is more difficult, as the warping of the magnetic field causes a non-uniform reduction in angle sensitivity. A distortion matrix, ellipsoid fitting, or other characterization of sensitivity vs. orientation must be employed.

Both hard and soft iron distortion may vary over time, as parts become magnetized, or introduced by the surroundings. InvenSense utilizes “in-use” calibration algorithms to adjust for changes during run-time, providing best performance for a variety of environments.

As of eMPL 5.1, InvenSense compass calibration algorithms include:

- Soft Iron Correction: A module which generates a mapping of spherical magnetometer data: tracking center shift, and scaling axes according to sensed data. This correction reduces the effect of soft iron distortion introduced by device design, and may be triggered to recalibrate based on device configuration changes.
- Hard Iron Correction: A compass vector calibration module continuously estimates the compass bias and radius during run time.

4.3 Electric Current Noise

Magnetic fields can be created by both AC and DC electrical current, or by changes in the electric field. Electromagnetic noise will be picked up by the magnetic sensor as noise on the magnetic field. The magnetic sensor should be located away from the source or traces containing current fluctuations as detailed in Table 4.1.

Current Fluctuation [mA]	Recommended Distance* from Trace [mm]
2	0.2
10	1
50	5
100	10
200	20

(*) distance where fluctuation of magnetic field is below +/- 2µT

Table 4.1: Recommend distance from fluctuating current traces

4.4 Heading Calculation for Compass Applications

A simple calculation of the earth’s magnetic field can be obtained by calculating the angle of the X and Y axis magnetic fields as sensed by the magnetometer:

$$Heading\ Angle = \operatorname{atan}2(Y, X).$$

For applications which require an accurate heading angle, this approach is not sufficient. Using this simplified method, the heading angle is highly dependent on the orientation of the MotionTracking Device. As the Earth’s magnetic field is sensed as a 3-dimensional vector, the simplified calculation is only accurate when the earth field vector is aligned with the magnetometer’s XY plane. This is not typically the case, as the earth field has a significant magnetic inclination (or magnetic dip), which is geographically dependent. For example, within the Continental United States, this inclination angle can vary between 55 and 75 degrees. Because of the high inclination angle, the heading output will be extremely sensitive to small changes in pitch and roll when rotating the device on a flat plane.

A much more accurate calculation includes rotating the sensed magnetic field to a horizontal plane prior to computing the heading angle. For static measurements (when the device is stationary), an accelerometer reading is sufficient to estimate roll and pitch, while during dynamic movements, the orientation output of Motion Fusion is recommended.

Quaternion rotation may be applied to the magnetometer data, or calculation using Euler roll / pitch angles, using the following example:

$$X' = X * \cos(pitch) + Y * \sin(roll) * \sin(pitch) - Z * \cos(roll) * \sin(pitch)$$

$$Y' = Y * \cos(roll) + Z * \sin(roll)$$

$$Heading\ Angle' = \operatorname{atan2}(Y', X')$$

4.5 Evaluation of magnetic sensor performance

When installed within a device, the magnetic field can be evaluated by analysis of sensor angular accuracy and noise.

The standard deviation of magnetometer data (noise) should be less than 1 uT for raw data, so that digitally filtered data can be below 0.5 uT and reported at a high data rate. A noise level of 0.5 uT corresponds to a typical angle deviation or jitter of 0.5 degrees.

Angle accuracy can be measured by analyzing the heading angle of the sensor relative to its orientation. At precise rotations, the output and device orientation can be compared. Typical angle accuracy of +/- 2 degrees is reasonable for a calibrated magnetometer in consumer device applications.

Alternatively, a Helmholtz coil can provide a reference magnetic field signal for angle accuracy measurements, rather than rotating the device. A Helmholtz coil passes current through two coils of wire, placed at a precise distance, equal to the radius of the two coils, as shown in figure 4.5. The magnetic field generated near the center of the coil has a uniform value over a significant volumetric space. By using a multi-axis Helmholtz coil, the generated field can be rotated around a device precisely, independent of any environmental sources.

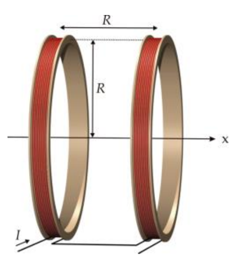


Figure 4.5: Example of Single Axis Helmholtz Coil

5. Accelerometer and Gyroscope Design Guidelines

5.1 Package Stress

MEMS accelerometer and gyroscope motion processors are mechanical devices and are affected by package stress. Bending in the PCB caused by mounting locations, screw holes, or misalignment will transfer board stress to the package, and can alter the output of the MPU, or in extreme cases may even damage the MEMS structure.

The MPU should be placed in a location where there will be minimal board stress. Typically, this is away from any fixed mounting location, screw hole, or large insertion components, such as buttons, shielding boxes, connectors, etc. During the design phase, the estimated misalignment, mounting method, and board geometry may be used to determine the areas which have the least internal stress, through static or finite element analysis.

Package stress can also be introduced from thermal sources during soldering or reflow processes. Uneven thermal expansion and cooling during the assembly process introduces this stress. It is recommended not to exceed the conditions in the reflow diagram provided within the device's Product Specification document. This diagram represents maximum conditions required for component reliability testing. Typical lead-free reflow solder processing is conducted between 235°C and 260°C.

It is recommended not to hand solder the MPU, as the uneven application of heat during soldering may introduce an undesired bias offset in the part. Do not place any component pads or vias within 2mm of the package land area, in order to ensure even cooling and minimal mechanical coupling between the MPU and adjacent devices.

Any epoxy-sealed parts on the board should be placed away from the MPU such that the epoxy resin does not come in contact with the package. Curing shrinkage or uneven thermal expansion may introduce package stress and adversely affect the sensor output.

Keep the distance from the MPU more than 15mm away from bridges for PCB separation by router (fig. 5.1). Deflection from a routing drill or saw can damage the MEMS device. Similarly dull router bits and saw blades can cause excessive mechanical vibration; which should be avoided. Do not snap apart panelized boards, since snapping apart the PCB boards may introduce severe bending forces and mechanical shock which may damage the MPU.

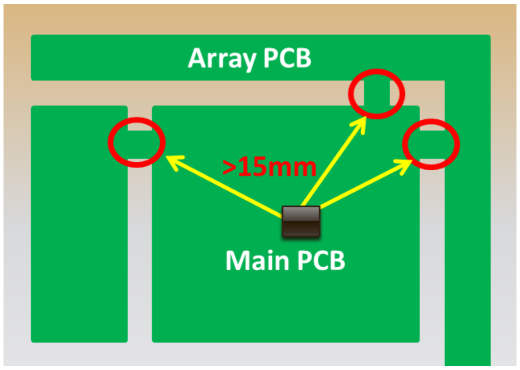


Figure 5.1: Recommended distance from panelized PCB bridges

Do not place connectors or test points for Pogo pins on the PCB surface below the MPU location, as in figure 5.2. Deflection and shock from snapping the connectors and pressure from the Pogo pin during functional test on a production line may damage the MEMS part.

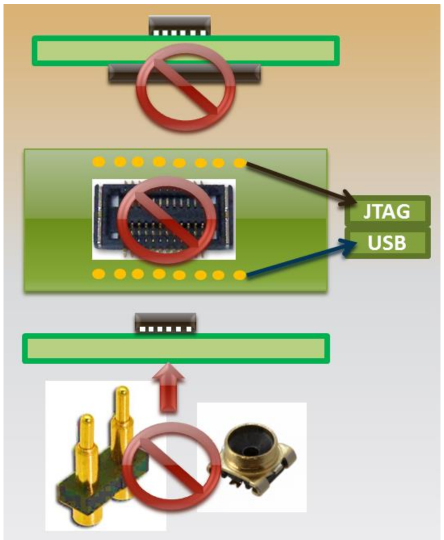


Figure 5.2: Avoid connectors directly behind the board

5.2 Thermal Requirements

The internal measurement of the MEMS sensor is dependent on temperature. For InvenSense MPU devices, software based temperature compensation is available, however, variations in device temperature may cause changes in sensor accuracy and should be avoided. Care should be taken for placement of the MPU relative to heat sources, which may include processors, power management circuitry, or high current devices. The temperature gradient across the MPU should be minimized for best results.

5.3 Exposed Pad Requirements

PCB land patterns are defined within the Product Specification document, and should be followed closely. The center Exposed Pad (EP), for MPU devices is a No Connect (NC) pad. To avoid package stress, do not solder the EP to the PCB. The EP is not required for heat sinking, and should not be soldered to the PCB. There is no electrical connection between the EP and the CMOS.

It is also strongly recommended to define a keep out layer beneath the MPU, and not place any trace, fill, or via on the top layer under the exposed pad, described in figure 5.3.

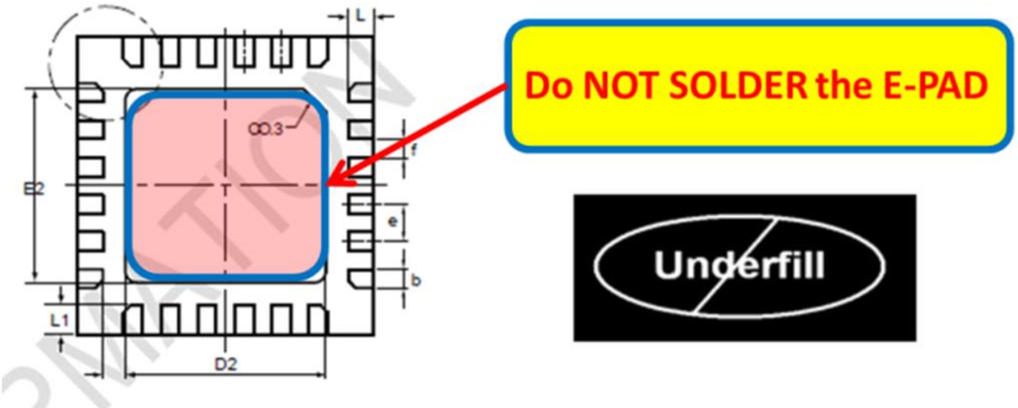


Figure 5.3: Exposed Pad (E-PAD) requirements

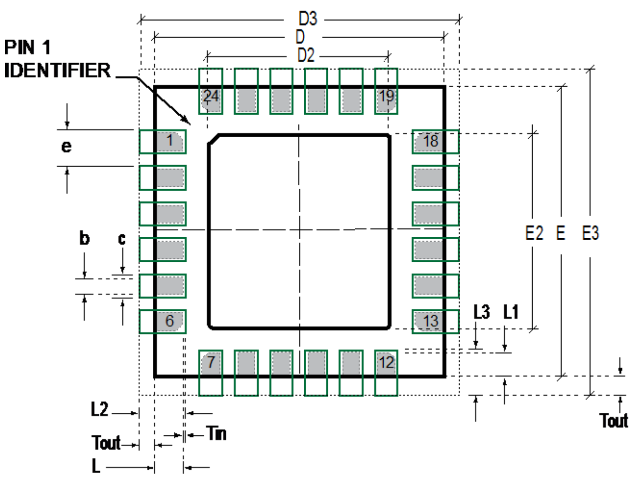
Except for the EP, a solder mask opening is required for all pin footprints. All pins should be soldered to the board to reduce uneven assembly stress, and the solder paste stencil should not have an opening for the exposed pad to prevent stress and pitch misalignment.

5.4 PCB Trace Layout

Traces connected to pads should be as symmetrical as possible. Symmetry and balance for pad traces will improve component self-alignment and lead to better control of solder paste reduction after the reflow process.

For high speed interfaces, such as I2C and SPI, all clock and data traces should be routed with the same length, and away from the serial bus or other high speed traces. Power traces should also be routed away from high speed signals, and kept 10mil or thicker for a 0.5oz copper PCB. Provide a solid ground return path, with traces 10mil or thicker for a 0.5oz copper PCB.

The PCB Layout Diagram and recommended pad size is provided within the MPU device Product Specification documents. Figure 5.4 below provides an example of a PCB Layout Diagram from PS-MPU-6000A-00 (revision 3.3). Please use the most recent revision of the product specification for the device that you are working with.



PCB Layout Diagram

SYMBOLS	DIMENSIONS IN MILLIMETERS	NOM
	Nominal Package I/O Pad Dimensions	
e	Pad Pitch	0.50
b	Pad Width	0.25
L	Pad Length	0.35
L1	Pad Length	0.40
D	Package Width	4.00
E	Package Length	4.00
D2	Exposed Pad Width	2.70
E2	Exposed Pad Length	2.60
	I/O Land Design Dimensions (Guidelines)	
D3	I/O Pad Extent Width	4.80
E3	I/O Pad Extent Length	4.80
c	Land Width	0.35
Tout	Outward Extension	0.40
Tin	Inward Extension	0.05
L2	Land Length	0.80
L3	Land Length	0.85

PCB Dimensions Table (for PCB Lay-out Diagram)

Figure 5.4: Exposed pad (EP) dimensions and sizing recommended for MPU-6050

Place vias outside of the solder area and near the pad, as they can cause elevation changes. Do not place vias within the pad outline; as vias and their related plating materials can contribute to an orientation offset and non-uniform mechanical package stress.

Eight NC (No Connect) pins can be soldered to the board for mechanical stability, but those pads on the board should not be connected electrically.

5.5 Noise Sources

Physical noise sources can cause unnecessary vibration and contaminate the desired measurement. The MPU should be mounted in a rigid location, which will have minimal external vibration.

Moving parts which cause vibration and are not intended to be measured, such as speakers, vibration/haptic motors, buttons, etc. (figure 5.5), should be mechanically isolated from the MPU.

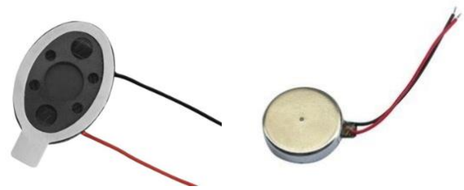


Figure 5.5: Speaker and tactile vibrations can be interpreted as noise by the MPU

Active signals may harmonically couple with the gyro MEMS devices, compromising gyro response. InvenSense MPU gyroscopic sensors operate at drive frequencies: X = 33+/-3 kHz, Y = 30+/-3 kHz, and Z = 27+/-3 kHz. To avoid harmonic coupling don't route active signals directly below or near the package. For best performance, design a ground plane under the EP to reduce PCB signal noise. If the MPU device is stacked under an adjacent PCB board, design a ground plane to shield the MPU from the adjacent PCB.

Electrical sources, such as a switched-mode power supply (SMPS) shown in figure 5.6, can cause high frequency vibration. SMPS with switching noise below 150 kHz (including Harmonics) can reduce device performance.

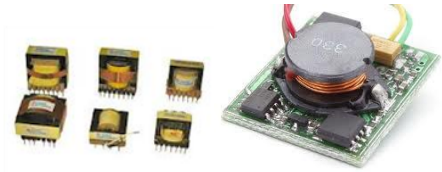


Figure 5.6: Switched-mode power supply circuitry to avoid

6. Analyzing Sensor Data Issues Due to Sensor Placement

6.1 Overview

As stated in the previous sections, sensor data will be affected by the location of the device and its surrounding components. This section describes the tools that can be used to analyze the sensor data, to characterize and correct issues of magnetic distortion, package stress, noise and thermal conditions. InvenSense recommends our customers contact their local InvenSense support team when the need to characterize devices using InvenSense MPUs arises.

6.2 Analyzing Sensor Data

When possible, the orientation of the device and magnetic data should be analyzed simultaneously, in order to characterize sensor angular accuracy.

6.2..1 InvenSense Sensor Test Tools

InvenSense software releases are packaged with test tools that provide the capability to collect sensor data at run-time. It is recommended to use the test tools provided by InvenSense to first verify if the sensor is responding correctly and the sensor data is within spec. Analyzing run-time sensor data will help in detecting problems with sensor performance.

6.2..2 Third Party Sensor Tools

Third party tools such as Microsoft's Sensor Diagnostic Tool or Traceview can be also used to collect run-time sensor data to detect problems with sensor performance. These tools provide capabilities to save the individual accelerometer, gyroscope and compass data to a comma separated (CSV) file. The CSV data can be analyzed and sensor data can be graphed to detect placement related problems.

6.2..3 Sensor Data Collection

InvenSense software has the capability to log sensor data to a file during device operation. The software provides the capability to collect raw as well as calibrated sensor data. This gives us the option to replay the sensor data at a later time and detect any errors due to placement issues.

Sensor data collected in this fashion can be post processed using mathematical analysis software to detect the effects of magnetic distortion, package stress, noise and thermal conditions, and assist in mitigation of those effects.

7. Quick Reference

This section is added a brief listing of PCB design guidelines which may be used in review when defining device placement. This list is not complete, nor reflects all information provided within this document.

Description		Issue	Corrective Action
Magnetic Distortion			
	Hard Iron	Saturation of magnetic sensor	Avoid placement near permanent magnetic fields
	Soft Iron	Angular error of magnetic field	Avoid placement near ferromagnetic materials
	Noise	Increased noise or jitter within magnetic field	Avoid placement near current fluctuation
	Compass	Coupling of device pitch and compass heading	Ensure compass heading is computed with three-axis data
Package Stress		Increased sensor offsets	Place part in a location of minimal PCB stress, do not solder Exposed Pad
Thermal Stress		Temperature variation of data	Avoid a thermal gradient across the part
Impact Survivability		Shock Failure, damage to MEMS device	Ensure surrounding surfaces will not impact MEMS device in event of shock

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