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An Overview of MEMS Accelerometers and Gyroscopes

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Abstract: MEMS (micro-electromechanical 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 video games and smart phones to catapult broad awareness of what inertial MEMS 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.

KEYWORDS: **MEMS, ACCELEROMETERS, GYROSCOPES, PROOF-MASS, MICROFLUIDIC MEMS, BIOMEMS, VIBRATION, TILT, ROTATION, SHOCK.**

I. INTRODUCTION

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro fabrication. The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters. Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move [2]. The term used to define MEMS varies in different parts of the world. In the United States they are predominantly called MEMS, while in some other parts of the world they are called “Microsystems Technology” or “micro machined devices”.MEMS are also referred to as micro machines (in Japan), or micro systems technology – MST (in Europe)[3].

II. MEMS TECHNOLOGIES

MEMS components can be classified into six distinct categories. These categories of MEMS are based on their application. These categories include:

- Sensors
- Actuators
- RF MEMS
- Optical MEMS

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Vol. 3, Issue 12, December 2017

- Microfluidic MEMS
- Bio MEMS

Sensors are devices designed to sense changes in and interact with their environments. Devices found in this class include chemical, motion, inertial, thermal, and optical sensors.

Actuators are devices designed to provide power or stimulus to other MEMS components devices. In MEMS, actuators can provide power using either an electrostatic or thermal stimulus.

RF MEMS are devices used to switch, transmit, filter, and manipulate radio frequency (RF) signals. Typical devices include; metal contact switches, shunt switches, tunable capacitors, antennas, tunable filters, etc.

Optical MEMS are devices designed to direct, reflect, filter, and/or amplify light. These components include optical switches and reflectors.

Microfluidic MEMS are devices designed to interact with fluid-based systems. Devices such as pumps, valves, and channels have been designed and fabricated to transport, eject, and mix small volumes of fluid.

Bio MEMS are devices that, like microfluidic MEMS, are designed to interact with biological samples. These devices are designed to interact with proteins, biological cells, medical reagents, etc. and can be used for drug delivery or other in-situ medical analysis.[4]

III. MEMS SENSOR GENERATIONS

***1st generation*:** These were used on silicon structure. It was a multi-chip approach where the sensing element was one chip and the signal processing electronics was on other chip. It gave an analogue output with some amplification on the microchip

***2nd generation*:** These combined the analogue amplification with an analogue- to – digital converter on a microchip

***3rd generation*:** In this phase, digital intelligence for linearization and temperature compensation were added.

4th generation: These include programmable MEMS, memory cells for calibration and temperature compensation [1]

IV. MEMS MOTION SENSORS

Accelerometers are microscopic silicon chips that can detect motion; they consist of a proof-mass that experiences inertial force. The force causes the proof-mass to move, thereby elastically deforming the suspension. An accelerometer can measure acceleration in three directions(X, Y, Z axis) *see Figure 1* and gyroscopes can measure rotation along three axes (yaw, pitch, and roll). The sensing mechanism decides the type of accelerometer, viz., piezo-resistive, capacitive, piezo-electric, tunneling, optical, resonant, thermal etc[2].

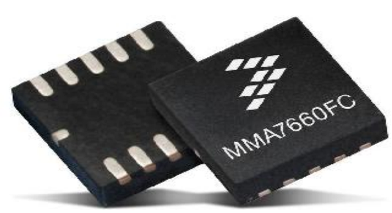

Figure 1: Freescale MMA7660FC 3-axis digital accelerometer

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Vol. 3, Issue 12, December 2017

Signal conditioning is used for converting the signal to an amplified analogue or digital signal. Thus the mechanical part used in sensing and the signal processing part forms the electronics of an MEMS chip. MEMS can be classified depending on the type of output-- analogue or digital. Normally, in an application/product, MEMS accelerometers/gyroscopes are used in combination with microcontrollers. Analogue output type MEMS can be used with microcontrollers with an in-built ADC, or the digital version can be used.[1]

V. TYPES OF MOTIONS

The success of motion sensing applications is driven by continuous innovation, creativity and development in micro-fabrication techniques. Motion sensing is a fairly old technology that was first used in aircraft navigation systems. With motion sensors currently taking the shape of micro-machines, it has captured the consumer market, making its way into products like mobiles, cameras, gaming consoles, security systems and many more.There are mainly five types of motion that can be detected with a variety of accelerometers and gyroscopes which can be innovatively used in wide range of applications. These are -

- Acceleration
- Vibration
- Shock
- Tilt
- Rotation.

The first four types display some kind of linearity and acceleration and are measured by accelerometers. Rotational motion are detected by gyroscopes[1].

VI. MOTION SENSING FOR APPLICATION DEVELOPERS

A motion sensor can be used for multiple applications in the same product figure 2 describes various elements of motion sensing that can be useful for an application in a particular device. Applications are usually software programs that produce a reaction to a sensed motion signal from the accelerometer or gyroscopes. Designers opt for high-end MEMS sensors in order to develop multiple applications in the same device. Each of the applications requires different data sampling rates and anti-aliasing measures that ensure data accuracy through different filters for a particular application.

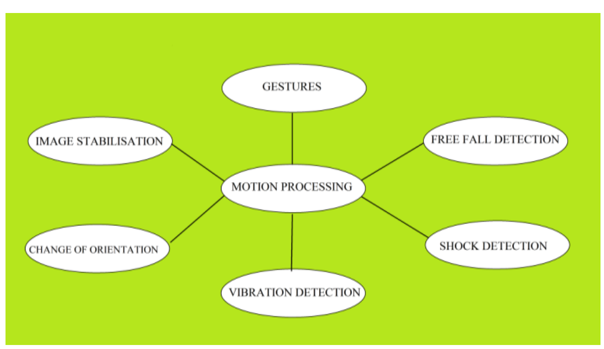

Figure 2: Types of motion processing

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Vol. 3, Issue 12, December 2017

Acceleration in Usability and Power Management

Acceleration also 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 and replacing the battery. An intelligent remote control with a backlit LCD is among the potential scenarios.[4]

Figure 3: Acceleration example, sensing of movement and position: The PocketCPR

*The **PocketCPR** device is used to assist a rescuer in the delivery of high-quality CPR chest compressions. An ADI MEMS accelerometer provides the crucial sensor function to measure the depth and rate of chest wall movement during each compression, a critical element for reliable real-time performance during CPR.*

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[6].

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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 effort and drive up its electricity bills or eventually lead to damaged equipment as well[10].

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Vol. 3, Issue 12, December 2017

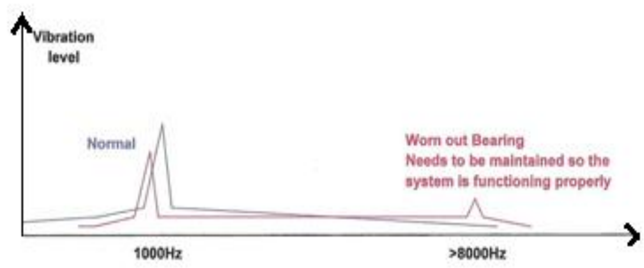

Figure 4: vibration example: machine health and bearing wear

Vibration in rotating machinery typically occurs at frequencies from 6 to 10 KHz. Vibration sensing using MEMS accelerometers is becoming an important alternative to conventional sensing approaches, as the demand for earlier and less costly predictive maintenance alternatives increases.

Shock, Gesture Recognition

The disk drive protection found in many notebook PCs is a widely implemented application of shock sensing. 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.

Figure 5: Shock example, IBM ThinkPad® notebook automatic hard drive protection

IBM's ThinkPad® notebook computers offered the first automatic hard drive protection technology of its kind using airbag-like MEMS crash sensors from ADI. Sudden acceleration in the notebook's motion triggers a signal to park the read/write head within 500 milliseconds before the notebook actually hits the floor.

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.

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Vol. 3, Issue 12, December 2017

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[5].

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 global positioning system (GPS) 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[5].

Figure 6: Tilt sensing example, Omron Wrist blood pressure monitor with advanced positioning sensor

ADI's MEMS accelerometer enables precise tilt inclination measurement of the user's forearm so when the blood pressure monitor is located correctly at heart level the cuff starts to inflate for more accurate blood pressure measurement through cuff position sensing.

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 six degrees of freedom (6 DoF). This brings ultra-fine 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[5].

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VII TYPICAL APPLICATION AREA

A designer has to carefully analyse various parameters such as number of axes, sensitivity, full scale, bandwidth, footprint and of course the price. The product designer needs to analyse the requirements and make a proper selection of the MEMS sensor[1].

Navigation: Motion sensing as first put to use in the navigation system of an aircraft. The main elements of a navigation system involving motion are orientation, velocity and position. These are efficiently provided by a combination of accelerometers and gyroscopes accelerometers detect the slope gradient by measuring the change in gravity, wheras gyroscopes give accurate position. Navigation systems are used in aircrafts, in the inbuilt GPS systems of vehicles as well as external navigators[1].

Gaming: *Gaming* involves a lot of control actions that are triggered by different motions. Many gaming consoles use motion sensors to control the gaming characters, creating a more interactive user interface.
The most popular gaming controller Nintendo's Wii, works on invensense's MEMS rate gyroscopes. The sensor measures the rate of rotation along the three axes[1].

Mobile handsets**:** Apple's IPhone, Nokia HTC, LG, Sony Ericsson and almost all Smartphone's have MEMS based accelerometers as an integral part of their hardware design. Software applications that use the signals from the motion sensing microchip have converted the conventional mobile handset into powerful 3D intelligent devices. Motion sensing has become the 'must-have' function in mobile phones and PDAs.
Nokia's N95 was the first to have an accelerometer chip, but Apple's IPhone made the application popular.

Medical equipment**:** Pressure sensing is a big feature for numerous medical applications. BioMEMS is being talked about as another promising area in micro-fabrication and micro-fluidics technologies. MEMS sensors can sense the motion in context and take appropriate action. Their miniaturization, accuracy and reliability are the key features that make MEMS suitable for medical implant devices like pacemakers. Motion sensors are used for invasive as well as non-invasive blood pressure measurement. Sensors can be embedded on a watch or any wearable device to continuously monitor and generate feedback. Surgical equipment widely uses these for better results[1].

Automobiles: MEMS-based accelerometers and gyroscopes are placed in different parts of car for a variety of applications. These sensors are ideal for their unique combination of stability, reliability, high sensitivity, low cost, compact size, wide range and high quality. These sensor give digital outputs that can be fed to the central microprocessor for it to perform the complex reactive function.
The tilt sensor in electronic parking brake systems automatically activates the parking brakes to prevent the slipping of the car. A computerized system based on motion sensors and actuators called Electronic Stability Control (ESC), is used to enhance the safety in vehicles. In BMW X5, the MEMS sensors collect data while the car is being driven and signals the suspension and healing to adjust automatically MEMS- based pressure sensors are also used in automobile combustion systems and power trains[1].

Consumer Electronics: Vivid forms of motion can be useful in a variety of consumer electronics goods. Industry leaders in this domain have realized the potential in MEMS-based accelerometers and are now tapping the market with innovative applications. Music players from Sony use the 'Shake-Up' feature to shuffle the songs. Gestures are also used to scroll and go to the next playlist[1].

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Vol. 3, Issue 12, December 2017

VIII CURRENT CHALLENGES

Some of the obstacles faced by organizations in the development of MEMS and Nanotechnology devices include:

Access to Fabrication

Most organizations who wish to explore the potential of MEMS and Nanotechnology have little or no internal resources for designing, prototyping, or manufacturing devices, as well as little to no expertise among their staff in developing these technologies. Few organizations will build their own fabrication facilities or establish technical development teams because of the prohibitive cost [7].

Packaging

MEMS packaging is more challenging than IC packaging due to the diversity of MEMS devices and the requirement that many of these devices need to be simultaneously in contact with their environment as well as protected from the environment. Frequently, many MEMS and Nano device development efforts must develop a new and specialized package for the device to meet the application requirements. As a result, packaging can often be one of the single most expensive and time consuming tasks in an overall product development program [8].

Fabrication Knowledge Required

MEMS device developers must have a high level of fabrication knowledge and practical experience coupled with a significant amount of innovative engineering skill in order to create and implement successful device designs. Often the development of even the most mundane MEMS device requires very specialized skills. Without this expertise and knowledge, at best device development projects can cost far more and take much longer. At worst, they can result in failure [7].

IX CONCLUSION

MEMS components are extremely diverse in their application and function. MEMS business continues to be driven by innovation. A major part of the business still comes from automobile applications, but consumer electronics is seen a potentially the biggest growth driver for MEMS devices. MEMS-based products will continue to be in demand for their high-end user interface and motion sensing that can be applied innovatively to novel applications [1]. To achieve this, industry will have to work with academia and government institutions to create the knowledge base required for tool and technique development for global and local defect localization [9].

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