Markets and applications for MEMS inertial sensors

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ABSTRACT

The ability to meet demanding specifications and stringent price points continues to drive market insertion for MEMS inertial sensors in cost-sensitive automotive applications and more recently, consumer markets. This paper examines major markets and drivers for gyroscopes and accelerometers, which will grow from a total of $835 million in 2004 to almost $1350 in 2009, a CAGR of over 10%.

Keywords: MEMS, inertial sensors, accelerometers, gyroscopes, inclinometers, markets, applications

INTRODUCTION

For many years, gyroscopes and accelerometers have been employed for inertial sensing in civil and military aerospace, transportation systems and space applications. For high precision applications such as inertial guidance, ring lasers and fiber-optic gyroscopes with a bias drift rating of 1°/h are used. MEMS sensors are also attractive for inertial navigation, in general due to weight, size and cost considerations. Indeed, opportunities exist for precision MEMS gyroscopes in navigation units deployed in short to medium range projectiles, where their compact size and low weight allow more explosive to be packed into a missile. Further applications comprise unmanned aerial vehicles (UAV) and munitions having somewhat relaxed bias drift requirements.

MEMS devices, e.g. for munitions, are required to be 'gun hard' and must typically withstand anywhere from 10,000 to 20,000 g, while retaining overall stability. MEMS inertial navigation units are much cheaper than ring or fiber optics solutions and typically cost around $1,000-2,000 for short-range projectiles.

Figure 1: MEMS capacitive accelerometer designed for gun hard munitions, ground drilling, precision guidance, etc. (Courtesy Colibrys)

To improve the stability (and therefore range) of such MEMS inertial navigation units, many companies and institutes are seeking to demonstrate gyros with better 10°/h, compared to 100°/h today. And although military avionics set demanding requirements that cannot be met by MEMS technologies, MEMS gyros and accelerometers have recently been qualified for small aircraft within Attitude Heading Reference Systems (AHRS). Crossbow is currently the main supplier of integrated AHRS systems, which feature three gyroscopes and three accelerometers. Other suppliers of inertial sensors to aerospace, defence and geophysics applications include Honeywell, Colibrys, ENDEVCO, BEI Technologies, LITEF (Northrop Grumman) and Tronics.

Functionally, gyroscopes are used to sense angular rotation with respect to a reference system. When rotated, the vibrating mechanical element (resonator) experiences the Coriolis acceleration effect, which causes secondary vibration orthogonal to the original vibrating direction. This secondary vibration allows the angular rate to be deduced. Almost all reported MEMS gyroscopes use vibrating mechanical elements as the proof-mass to sense the rotation, and measure yaw rate (motion around the vertical axis) rather than the absolute angle.

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In an accelerometer, each axis is equipped with a sensing element such as a moveable mass, whose movement in relationship to a fixed element is detected and recorded. This is achieved either by measuring a shift in electrical capacitance, or via a piezoresistive element placed onto the spring and linking the moveable and the fixed element together. This measured change is subsequently converted by signal electronics (either integrated onto an ASIC chip or placed on a separate chip) into an analog or digital signal that is proportional to acceleration. Sometimes called inertial or motion sensors, accelerometers measure tilt and inclination, shock, vibration, and inertial acceleration.

After defense inertial navigation applications, the automotive industry is the main beneficiary of MEMS inertial sensors. Early on, automakers seized the opportunity afforded by MEMS to develop robust low-cost sensors, first for airbags, now for an ever larger battery of sensors that assist in providing better road stability and cornering safety (vehicle dynamics) or navigation. In fact, many mid-range cars now feature as many as 50 different sensors (one third of which are MEMS) and luxury vehicles over 100 (1).

More recently, inertial sensors have begun to penetrate commercial applications. Leveraging the technical advances in MEMS sensors and aggressive price reductions afforded by the automotive industry, MEMS accelerometers already offer new features for mobile phones, cameras, camcorders, advances sports items and toys, etc. and will represent a significant market opportunity by the end of the decade.

There are many other opportunities for MEMS based inertial sensors. Many are fragmented and represent only small markets. Examples are gyroscopes within stabilized platforms used for mobile antenna dishes, remote control vehicles, simulators (gaming or training stations), or in wheelchair stabilization, agricultural vehicles (tractors), marine satellite compasses, physiotherapy and therapeutic equipment to analyze motion and aid recovery as well as interface devices such as 3-D pens and gloves.

Accelerometers can be used in many of the same applications, and also those that monitor horizon (inclinometers) or any kind of shock (e.g. goods shippage monitoring, black boxes, industrial drills, robots and platform stability applications, etc.) or vibration monitoring in industrial environments (road compacting), not to mention tilt. Simple inertial sensors also prevail and the use of MEMS sensors is dictated by the precision required and cost.

A number of other niche markets could also emerge for MEMS gyros in oil exploration and civil engineering projects, mainly for precision drilling measurements (tunnel construction). Micromachined gyros can be used in the analysis of motion in sports and also monitoring of recovering limbs, although opportunities in these applications are modest (typically << $25 million).

This paper discusses overall markets for inertial sensors, and subsequently breaks out and concentrates on significant opportunities for automotive safety and navigation, and emerging markets for inertial sensors in portable consumer electronics. The technical specifications and cost considerations for MEMS gyroscopes, accelerometers are also considered.

MARKETS FOR INERTIAL SENSORS

Overall, we expect the market for inertial sensors to grow from $835 million in 2004 to almost $1350 in 2009 (see figure 2). This equates to an overall growth rate of 10%. Currently about 80% of this market is for automotive applications, although the balance is expected to shift to about 60% as consumer applications begin to penetrate the market over the next 3-4 years. Gyroscopes recently edged ahead of sales of accelerometers, and markets for these devices are expected to outweigh accelerometers in future. Although the unit volumes are much lower, this reflects higher average component cost—a result of the greater manufacturing challenges associated with these devices. In 2004, a total of 27.5 million MEMS gyroscopes were shipped for a total value of $419 million, compared to about $407 million for accelerometers.

By 2009, the market for gyroscopes will grow to $718, mostly driven by automotive safety applications. Acceleration sensors will grow to $626 million overall, mainly for automotive safety but also consumer applications. Consumer applications represent the fastest growing sector and will exceed $300 million in 2009, mostly for motion sensing (games, screen scrolling, etc.) in cell phones, drop detect in portable electronics and image stabilization in image capture devices.

Prices vary widely by component type and specifications. A 2-axis ceramic piezoelectric gyroscope for consumer applications costs \$7-\$10[2] (e.g. Murata) for consumer applications in volume, while aerospace and defense applications command up to \$420 per gyro axis in modules that contain three gyros and accelerometers. Prices for gyros in space applications are even higher.

Accelerometers are typically about one fifth the price of gyroscopes per axis but are more widely deployed; in 2004 some 165 million accelerometers shipped with an average price of around \$3 or less, mostly for airbags. Accelerometers can cost \$100 to \$150 per axis for very high-end devices (e.g. space and defense).

We also note that around \$80 million worth of inclinometers were shipped in 2004, mostly for automotive applications, but also precision laser guidance, for example. Typically, inclinometers are a mix of thermal or micromechanical accelerometers used to measure static acceleration events (0-1g) or other systems such as liquid-based tilt sensors, and area not discussed in detail here.

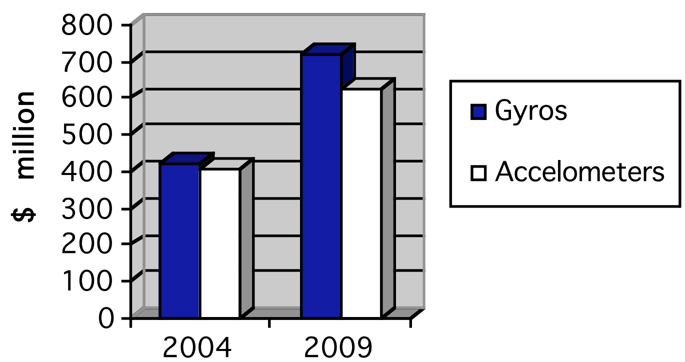

Figure 2: Markets for MEMS inertial sensors 2004 – 2009 (million \$)

In figure 3, we break out the market trends for the main applications. In order these are automotive, consumer, defense, and other (a large, fragmented mix including household, pacemakers and hospital beds, geophones, measurement-while-drilling, industrial robots, platform stabilization, etc.).

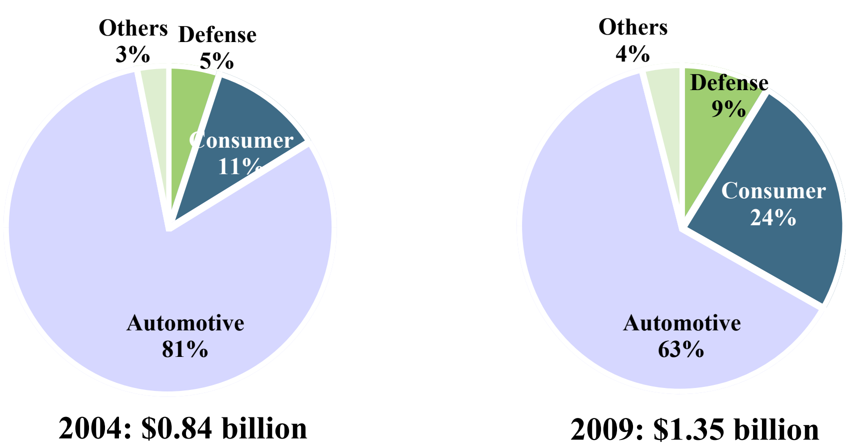

Figure 3: Markets and applications for MEMS inertial sensors 2004 – 2009 (\$ million)

2 All prices refer to a wafer level 1 packaged component.

1. Automotive

In the automotive sector, batch micromachining has reduced MEMS component sizes and provided low power consumption sensors that can be integrated with signal conditioning into small packages. Automotive markets currently account for more than 80% of total gyroscope sales, for example, particularly for rate grade (bias drift > 100-1000º/h) sensors employed in vehicle dynamics, roll detection and in-car navigation. Automotive applications can be harsh and operating temperatures vary from -40º to +85ºC. The emphasis is on manufacturing robust components with a high quality factor, and reliability extending over 10-15 years.

1.1. Applications and price considerations

Gyroscopes and accelerometers are used in the following applications:

- Vehicle Stability Control or ESP (dynamics) – yaw rate sensors with a resolution of 0.1º/s to mitigate under- and over-steering, typically including a low g single axis accelerometer (or sometimes two).
- Roll detection – devices with a resolution of 1º/s to trigger curtain air bags and to pre-tension seat belts in the event of rollover, with an accelerometer.
- Navigation – dead reckon assistance with a rate grade resolution of 0.5º/s to assist and improve the accuracy of Global Positioning System (GPS), sometimes with an accelerometer, but mostly a gyroscope.

1.1.1. Vehicle dynamics

Vehicle dynamics systems measure lateral slip and yaw rate in relation to the steering angle. The information is computed and used to stabilize a vehicle if it starts to skid, signaling the application of differential braking forces to the individual wheels and reducing engine torque (with the aid of a connection to the power-train controller). The result is a correction for over-steering or under-steering, particularly during severe cornering and on low-traction surfaces. Low g accelerometers (up to 2g) with high offset stability (100 mg) measure the lateral slip.

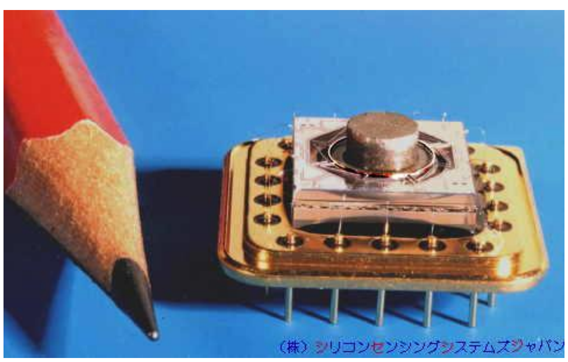

Figure 4: MEMS gyroscope from the company Silicon Sensing Systems, a joint venture of BAE and Sumitomo (photo courtesy BAE-SSS).

Tier one suppliers that build stability control systems for passenger cars include Robert Bosch, TRW Automotive, Delphi-Delco (e.g. the "Active Handling System" on General Motors' Corvette) and Continental Teves (using quartz gyros from BEI Technologies). The Robert Bosch system in the Oldsmobile Intrigue, for instance, costs about $600.

Robert Bosch and Continental Teves have been active in promoting awareness of vehicle stability technology. Continental recently reported that it expects to ship 1.2 million vehicle dynamic (ESP) units in the US alone in 2005 on 40 new models (2), an increase of 70% over the year before. According to BEI company reports for 2003, the company shipped over 3 million ESP modules worldwide. The leading supplier Robert Bosch stated it shipped 4 million units in 2004 (3). The company projects that North American sales of ESP systems will double in less than 2 years, from 11% in early 2005 to 23% of vehicles by the end of 2006.

SUVs are particularly prone to instabilities and roll over due to their high center of gravity. DaimlerChrysler will fit ESP systems to its 2005 SUVs, including Crossfire, Chrysler 300, Dodge magnum, and Jeep Grand Cherokee models. The company's Electronic Rollover Mitigation System will also appear on the 2005 Jeep Grand Cherokee.

The MEMS gyroscope module is estimated to comprise around 10-20% of the total cost of a vehicle dynamic system, and typically includes a yaw rate sensor, accelerometer, wheel position sensors, steering wheel sensor, pressure sensors, control unit, and hydraulic modulator. Depending on how the gyro is supplied and the technology, prices range from $15-75. The average selling price for an automotive gyro (sensing element, ASIC in a wafer level 1 package) is estimated to be $21. The price will erode to around $17 or less in 2009. Accelerometers are closer to $5 for a 1-axis unit.

1.1.2. Roll detection

Roll detection sensors rely on a gyroscope to determine the angle and roll rate of the vehicle around the longitudinal axis. When a critical angle is exceeded, the sensor signals a trigger for inflating the side curtain air bags and pre-tensioning the seatbelts. A low g accelerometer is incorporated to determine the vertical axis acceleration rate, as some banked curves can be interpreted as a possible roll over event. A second accelerometer is sometimes used to measure lateral slide, which can't be resolved by a side crash airbag accelerometer, if fitted. This measurement this already incorporated if the system includes vehicle dynamics, and rollover detection are sometimes included as part of vehicle dynamics systems.

The gyro in a roll detection system does not require the same resolution as yaw sensors for vehicle dynamics because roll rates are around five times larger (4), although a key requirement is excellent resistance to external shock and vibration. Prices average $13 and $5 for the gyroscope and accelerometer, respectively.

1.1.3. Navigation systems

Navigation systems rely on the use of a compass, databases and a GPS system. When the system is started and the initial direction is established, inertial data supplied by a gyroscope is used to determine when and how much the car has turned, until the direction can be verified and updated via map matching and GPS signals. Accelerometers can also be used to assist in GPS dead spots by providing dead reckoning calculations of distance. However, gyroscopes are expected to prevail over accelerometers in those GPS systems that feature an inertial navigation aid, with the exception of the Hertz "Never Lost" system.

Japan is currently the major market for GPS navigation systems, where over half of all new vehicles (2.5 million units) are fitted with these systems. Japanese cities suffer from complicated street networks (often without names) and finding a destination is considerably enhanced by a GPS navigation aid. The market is saturated in Europe and limited to high-end vehicles, although this situation might change if proposed European Commission legislation mandating the use of Telematics is introduced. Such systems – which feature a GPS navigation device and mobile communication unit – are used to automatically notify authorities of an accident (5). Even if accepted, this legislation is not expected to impact inertial sensor markets (which provide GPS dead-reckoning assistance) until after 2009.

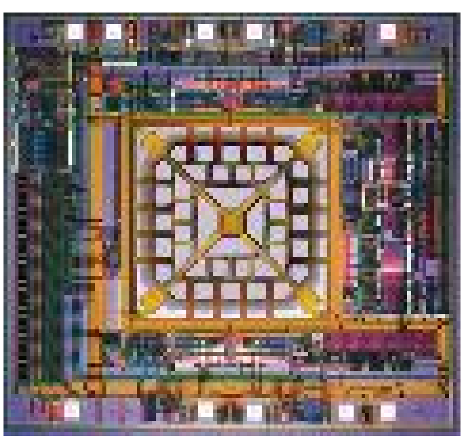

Figure 5: MEMSIC dual axis accelerometer fabricated on a monolithic CMOS process with integrated digital interface IC. (Courtesy MEMSIC).

Although standard in many luxury vehicles, the North American market for in-car navigation systems is relatively small. A number of gyro-equipped units have so far been supplied to urban bus lines. Prices average $11-12 for the gyroscope in a navigation unit because it is a non-safety critical device.

1.1.4. Airbags

The primary application for accelerometers in terms of unit sales is for airbag sensors. Indeed, airbags represent one of the most successful examples for the implementation of MEMS-based components. An airbag contains a MEMS accelerometer that detects frontal impacts resulting from large changes in acceleration (up to 100 g) and subsequently triggers the inflation of airbags in the driver and passenger seats.

Due to the much smaller crumple zone in car doors, side impact sensors operating up to 250 g and reacting within a few milliseconds have also become more widely used. It is also worth noting that MST-based pressure sensors are considered as alternative components for use in side impact detection systems.

1.2. Players and markets 2004 – 2009

MEMS-based gyros use vibrating mechanical elements to sense rotation. The materials employed include quartz and silicon, either bulk or surface micromachined. Silicon Sensing Systems (a joint venture company of BAE and Sumitomo in Japan) employs bulk micromachined silicon for its silicon vibratory gyroscopes. German manufacturer Robert Bosch, the leading automotive yaw rate sensor supplier, employs surface micromachined silicon-on-insulator processes for its vibratory gyro modules, which include the accelerometers.

Quartz based MEMS yaw rate sensors are manufactured by BEI Technologies (originally Systron Donner, now Schneider Electric) for both automotive and aerospace use. This unit is primarily sold to Continental Teves. The heart of the device is a double-ended tuning fork in an H configuration, which is fabricated from a single piece of pure crystalline quartz. Other inertial sensor suppliers include Denso in Japan, Analog Devices, MEMSIC (see figure 5) and VTI, and Infineon using gyros from SensoNor (Figure 6).

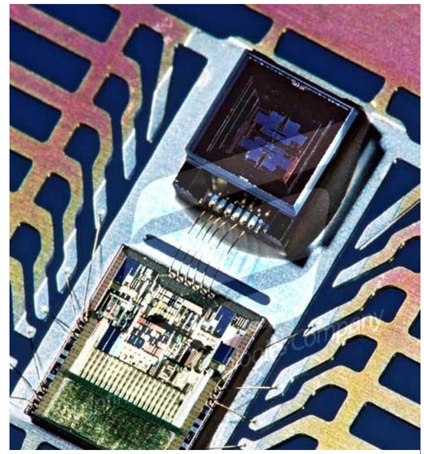

Figure 6: SAR-10 silicon yaw rate sensor for automotive roll detection (courtesy Infineon-SensoNor)

1.2.1. Markets

The automotive sensor market will grow from $676 million in 2004 to $854 million in 2009 (see Table). In this sector, MEMS gyroscopes for vehicle dynamics (sometimes called ESP or Electronic Stability Program) and accelerometers designed to trigger the inflation of airbags represent the largest market opportunities. However, while the number of airbags per vehicle is increasing, this is not necessarily reflected in the number of sensors, and this market will grow only in the next few years. The fastest growing applications are for vehicle dynamics, which use both yaw rate sensors and accelerometers (growing from $280 million to $382 million in five years).

Accelerometers	**$**	**Units (M)**	**Turnover ($M)**	**$**	**Units (M)**	**Turnover ($M)**
Airbag (mostly 1 axis sensor)	1.75	120.00	210.00	1.50	155.00	232.50
Vehicle Dynamics (mostly 1 axis sensor)	5.00	11.20	56.00	3.50	19.10	66.85
Tire pressure monitoring sensor	2.50	9.60	24.00	0.00	0.00	0.00
Roll detection (1 axis sensor), GPS navigation assist (2/3 axis sensor)	5.00	6.50	32.50	3.50	10.50	36.75
Active suspension (1 axis)	15.00	0.10	1.50	15.00	0.15	2.25
Gyroscopes						
Vehicle Dynamics (mostly 1 axis sensor)	20.00	11.20	224.00	16.50	19.10	315.15
Roll detection (1 axis sensor)	13.00	5.00	65.00	9.00	9.00	81.00
GPS navigation assist (1 axis sensor)	11.50	5.50	63.25	8.00	15.00	120.00
Total		**169.10**	**676.25**		**227.85**	**854.50**

Table 1 Market breakout MEMS sensors in automotive applications 2004-2009.

Some trends over the next few years include possible clustering of inertial sensors (with a potential for 6 degrees of freedom) to collect information on yaw rate, roll, and for navigation dead-reckon assistance. BEI Technologies has developed a four-degree of freedom module with two gyros and two accelerometers. Tire pressure monitoring systems (TMPS) currently feature accelerometers (to inform the RF transmitter to signal the tire's pressure only when in motion to save battery power) will vanish from most systems by 2009. Other potential replacement scenarios include body sound ultrasonic sensors to replace high-g accelerometers to determine and react appropriately to different kinds of crash. Siemens VDO is developing "Crash Impact Sound Sensing", intended for introduction in 2007, where supplementary information may be fed to safety systems using future camera or radar configurations.

2. Consumer portable electronics

2.1. Applications and price considerations

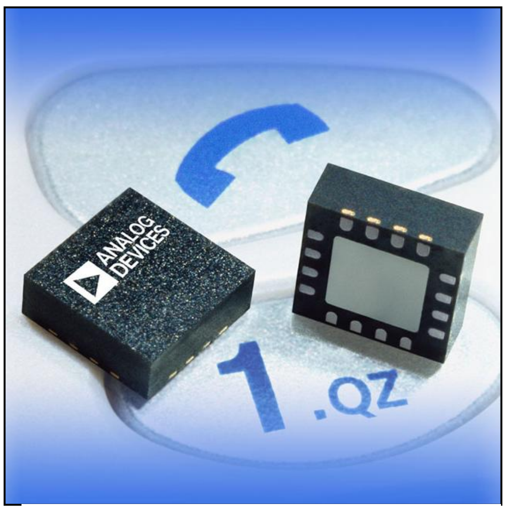

Figure 7: Analog Devices 5g dual-axis, analog output accelerometer intended for cell phone and other applications (Courtesy ADI).

Both gyroscopes and accelerometers are used for motion sensing in consumer and portable electronic devices, although accelerometers with 2 or 3-axis detection and on-chip signal analysis ASICs are likely to dominate over gyroscopes for reasons of cost. While currently closer to $4, the target price of $1.50 for a packaged 3-axis accelerometer (including signal conditioning ASIC) is expected for consumer applications, especially for mobile phone applications. The technology push is great, as the mobile phone market is predicted to top 1 billion units by 2009. The estimated market for MEMS in 2009 equates to only 10-20% of this potential opportunity.

MEMS gyros are incorporated in a variety of consumer goods such as camcorders and high-end digital cameras. Panasonic employs gyros in 20% of its video capture devices, for example. More digital cameras will feature video capability in future and this represents an additional potential market for image stabilization. Lower cost MEMS gyros are in development for consumer and other applications, but are likely to cost more than $2-3 per axis. Companies developing low cost, high performance MEMS gyros include Samsung and OKI, and InvenSense.

Figure 8: The Segway uses 5 silicon MST/MEMS gyroscopes from Silicon Sensing Systems (Courtesy BAE)

Overall, consumer applications today provide only small market opportunities for gyros. An exception is toy robots; Sony's AIBO dog costs several thousand dollars and has sold well over 500,000 units since its introduction. The attraction for MEMS manufacturers is the large number of different sensors required. The Segway personal transporter (figure 8) for example contains five silicon gyros from Silicon Sensing Systems (a BAE Systems and Sumitomo Precision Products joint venture).

Generally, the big opportunity exists for low g accelerometers within portable consumer electronics products. A small change in force of 1-2 g occurs when a device like a cell phone, MP3, or PDA is either tilted or moved in some fashion. The resultant signal has a signature that can be sensed using a MEMS inertial sensor. This signature can be programmed as an interface command, allowing gestures to control the functionality of cell phones and other similar personal devices.

Cell phone games (e.g. using sensors to detect tilt motion) are potentially one of the largest drivers for accelerometers in future. Companies like Freescale, Analog Devices and VTI provide multi-axis accelerometers for this application. Accelerometers enable multi-axis motion sensing functionality and can be combined with GPS systems to provide position information, and also to recover stolen devices like laptops by calculating a new location from a previous GPS reading. Using single or dual-axis accelerometers, power saving functionality (the sensor signals a wake up mode) and tap-based “muting” are additional features that could further excite the market.

To date, there are several examples of accelerometers in mobile phone applications. NTT DoCoMo has incorporated a pedometer, while Mitsubishi provides auto picture rotation and Nokia has introduced a gaming mobile.

Image stabilization in video cameras and more expensive digital cameras represent further market opportunities for accelerometers (and gyroscopes). Such devices are used to detect the level and direction of shake and counterbalance these movements to help stabilize the resultant image. For such applications, a 2-axis or 3-axis acceleration sensor transmits motion information to a processor built into the camera lens, which in turn directs the corrector motors to shift accordingly in real time. Software solutions are also used. Finally, in home theatre projectors, so-called “keystone correction” are also an application for 2-axis accelerometers.

Another interesting application of inertial sensors is **“**freefall” detection of portable devices such as MP3 players and laptops in order to protect hard disc drives (HDD). A 2-axis accelerometer (or 3-axis, in the case of Apple Macintosh’s “PowerBook”) senses when the laptop is in a free-fall (or zero g) condition. When this state is detected, a command is sent to park the head in order to avoid damage to the disc. IBM’s “ThinkPad” and Toshiba’s “EasyGuard” laptops also deploy accelerometers for drop detection. Some hard disc drive subsystem OEMs believe that all sub-2.5 inch drives will in time require such sensors.

To date, a number of MP3 players (e.g. Apple “IPOD”) employ an accelerometer in the HDD, as do digital camcorders with HDD storage (e.g. Toshiba). The reaction speed for a 1-inch 4GB storage unit from Toshiba is 2-5 ms, allowing ample time for a microcontroller ASIC to interrogate the signal to distinguish a drop condition from other movements such as running or dancing, and if necessary park the head. US-based company Cornice specializes in small HDD units and makes a 4GB system with a slot for an accelerometer. This trend could grow to include other portable devices: Samsung launched the first cellular phone (the V5400) to feature a 1-inch diameter, 1.5 GB HDD in 2004.

Figure 9: Samsung launched a 1.5 GB cell phone featuring a 1-inch HDD in 2004. Motion sensors can be used to determine a drop situation to park the drive head (Courtesy Samsung).

2.2. Markets and players 2004 – 2009

In 2004, overall shipments amounted to 22.65 million units with an average selling price of $4. Today, accelerometers are predominantly used to protect the hard disc of MP3 players and laptops, while gyros are mostly employed in image stabilization applications. Image correction for home theatre projectors also contributed to this market. While cell phones (e.g. gaming, battery saving and intuitive motion-based screen navigation) are expected to represent the significant opportunity for accelerometers in 2009, this market had yet to take off as of 2004.

	2004			2009		
Accelerometers	**$**	**Units (M)**	**Turnover ($M)**	**$**	**Units (M)**	**Turnover ($M)**
Mobile phone (2 or 3 axis sensor)	2.60	0.45	1.17	1.35	89.35	120.62
MP3 player (2 or 3 axis sensor)	2.60	11.20	29.12	1.65	24.65	40.67
Camcorder, games, joysticks, toys, sports, robotic toys, projectors, tilt compass (mostly 2 axis)	3.20	1.22	3.90	1.65	9.00	14.85
Notebook, Tablet PC (2 or 3 axis)	3.90	4.00	15.60	1.35	26.60	35.91
Gyroscopes						
Camcorder / Digital still camera image stabilization (2-axis)	7.00	5.20	36.40	4.40	11.00	48.40
Cell phone camera (image stab. 2 axis)				4.00	11.00	44.00
Robotics toys, 3D mouse, Segway, tilt compass…(average 2 or 3 axis)	14.00	0.58	8.12	8.20	2.27	18.61
Total		**22.65**	**94.31**		**173.87**	**323.07**

Table 2: Market breakout for inertial sensors in consumer and portable electronics applications 2004-2009.

Overall, the combined market for accelerometers and gyros for consumer applications will more than triple in 2009. By this time, close to 173 million sensors (mostly 2- and 3-axis, equivalent to a weighted total of 377 million axes) will be delivered with a total market value of around $323 million. An average price of $1.35 is assumed for a tri-axis accelerometer sensor. Gyros are expected to cost about $2 per axis or more (in high volume). Companies developing low-cost gyros solutions (e.g. using wafer-level approaches) include Samsung and InvenSense, in addition to NEC Tokin and Melexis.

The biggest growth opportunity is for accelerometers in mobile phones, followed by image stabilization using gyros to correct for shake in digital cameras, high-end camera phones (e.g. > 3 megapixel) and camcorders, although dual-axis accelerometers are also used in image stabilization (e.g. Freescale), or even software-based approaches. For this type of sensor, the consumer opportunity is expected to grow from almost nothing to $120 million by 2009 in mobile phones alone—or about one third of all inertial sensors used in consumer and portable consumable electronics.

Generally the mobile phone market, e.g. for motion sensing functionality like screen scrolling, gaming and intuitive menu scrolling, will be enabled by deployments of low g tri-axis accelerometers featuring a digital output. Such devices are challenging to manufacture but are already available from companies such as VTI, Freescale Kionix, Analog Devices, Hitachi Metals, STMicroelectronics, OKI and Robert Bosch. Traditionally an automotive supplier, Robert Bosch recently set up a subsidiary called Bosch Sensortec dedicated to consumer applications for MEMS sensors.

Furthermore, as mobile phones converge into "mobile terminals" that serve as phone, PDA, MP3 player, gaming console, GPS navigation aid, and camera, it is envisaged that 3-axis accelerometers could enable additional functionality such as drop detection, battery saving, menu scrolling, and gaming. With GPS, the accelerometer acts as an anti-theft device and location sensor. This will increase the return on investment achieved per sensor and the attractiveness to integrators looking for product definition.

Riding on strong price pressures needed to access the mobile phone segment, low-cost accelerometers will also penetrate household and white goods markets. Maytag's "Neptune" series washing machine already employs accelerometers for vibration and load monitoring, for example. The market opportunity could eventually be considerable, although such devices must compete with simple, very low cost switches.

Some interesting but so far niche consumer applications for accelerometers include “intelligent” mouse cursors like the “FinRing”, which uses a transmitter worn on the finger and a receiver USB-connected to a computer or play station to detect motion of the hand. Nintendo’s Kirby “Tilt-n-Tumble” GameBoy replaces input buttons with accelerometers to allow the user to tilt and shake to control the action. Microsoft’s game pad “Sidewinder Freestyle Pro” includes a 3-axis accelerometer. MEMS accelerometers for consumer applications are provided by Freescale, Analog Devices, Kionix, OKI and STMicroelectronics, and increasingly by automotive suppliers, namely VTI and Robert Bosch.

3. Conclusions

Markets for MEMS inertial sensors will grow at a healthy rate over the next few years. Sensors are no longer the privilege of luxury cars and more and more mid-range cars incorporate intelligent airbags, vehicle dynamics systems, roll detection and in-car navigation systems. As prices per axis drop below the $0.50 range, accelerometers will become an important feature of many portable consumable applications such as mobile phones, laptops, MP3 players, and PDAs. Eventually, other markets for household and white goods are likely to benefit from reduced costs in consumer electronics.

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