MEMS and Sensors Whitepaper Series

An Overview of MEMS and non-MEMS High Performance Gyros

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Whitepaper Topics: MEMS, non-MEMS, sensor, gyroscope, gyro, high performance, comparison, overview, motion, inertial.

About Us: TRONICS is an international, full service MEMS manufacturer with wafer fabs in Europe and the United States. TRONICS offers manufacturing services for a broad range of MEMS devices and delivers tested wafers, packaged dies or whole sensors, depending on customers' requirements. TRONICS' market share of the inertial MEMS foundry business reached 20% in 2011 (source YOLE Development).

Website: http://www.tronicsgroup.com

Introduction

Let us review the story of one of the most complex handheld sensing instruments built by mankind, namely gyroscopes.

This story started two centuries ago with the “Machine of Bohnenberger”. As shown in Figure 1, the first gyroscope was made with a massive sphere rotating thanks to three pivoted supports. It can be seen as a precursor of the Foucault Gyroscope. French physicist Leon Foucault first used his famous pendulum (a 28kg brass-coated lead bob with a 67 meter long wire from the dome of the Panthéon, Paris) to demonstrate the rotational rate of the earth in 1851, and then went on to perfect the measurement using a gyroscope in 1852. In order to grasp the underlying mechanics, one has to imagine that the plane of oscillation of the pendulum remains fixed relative to the distant masses of the universe, while Earth rotates underneath it.

Figure 1: Machine of Bohnenberger, as described in original publication of 1817.

During the 19th century, gyroscopes remained scientific curiosities. At the beginning of the 20th century, ships were increasingly built with steel, which sometimes resulted in poor performance of the traditional magnetic compass. This limitation of the compass for ship navigation drove the transformation of the gyroscope from the initial prototype device to a real product – gyros became the best solution to indicate the true (geodetic) north within a steel ship. The gyroscope was first patented in 1904 by a German scientist and inventor Hermann Anschütz-Kaempfe. Four years later, on the other side of the Atlantic, Elmer Ambrose Sperry patented the same type of device and established the Sperry Gyroscope Company. It is interesting to note that the Anschütz patent was contested by Sperry but, following an expert opinion provided by future Nobel Prize winner Albert Einstein, Anschütz was able to uphold his patent. The products from Sperry Gyroscope had a huge impact during the Second World War, as they were used in a large set of applications such as ship navigation, guided missiles, battery fire control, aircrafts artificial horizon and flight controls (Figure 2). By 1943, over 100,000 people worked for Sperry Gyroscope.

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Figure 2: Gyros used for German V2 rockets during World War II.

Since the end of the Second World War, gyroscopes have progressed from complex electromechanical devices assembled with more than 100 parts to the modern solid-state devices. Starting with ESG (Electrostatic Suspended Gyro), the progress has been enabled by the rapid adoption of new technologies: DTGs since the 1960s, RLGs since the 1970s, FOGs since the 1980s and MEMS since the 1990s. In the future, other exciting technologies such as cold atom interferometry, integrated optics and nuclear magnetic resonance may also be used in industrial applications.

Gyro nomenclature and definitions

In fact, “gyro” may refer to three different types of sensors. A gyro can:

1) Measure the angle of rotation (it is then called an angle gyroscope or gyroscope) or,

2) Measure the rate of angular rotation (it is then called a rate gyroscope or “gyromètre” in French) or,

3) Detect true (geodetic) north (it is then called a gyrocompass).

The difference is sometimes not obvious, because a single device may be used as a rate gyroscope as well as an angle gyroscope depending on its exact composition.

For the sake of simplicity, we will always refer afterwards to simply “gyros”, independently of the exact type of measurement performed.

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Overview of gyro technologies and performances

The leading gyro technologies presented in Table 1 represent 90% of the current high-performance gyro market.

Gyro technology	DTG	RLG	FOG	MEMS
Year of introduction	1960s	1970s	1980s	1990s
Principle	Coriolis force (Mechanical)	Sagnac effect (Optical)	Sagnac effect (Optical)	Coriolis force (Mechanical)
Number of parts	~70	~40	~30	3

Table 1: Overview of high performance gyro technologies

-Dynamically Tuned Gyros (DTG)
DTG is a mature technology for 2-axis high performance gyros. It is a small electro-mechanical device whose parts are made and assembled at very small tolerances.
Its operation principle is based on an inertial rotor suspended by a universal joint with flexure pivots. The flexure spring stiffness is independent of spin rate. However, the dynamic inertia from the gimbal provides negative spring stiffness proportional to the square of the spin speed. Therefore, at a particular speed, called the tuning speed, the two moments cancel each other, freeing the rotor from torque.
DTG is now considered as an obsolete technology, as it is too expensive, with extensive performance limitations and high power consumption.

-Ring Laser Gyros (RLG)
Although RLGs were first demonstrated in 1963, it was not until the 1970s that RLG came into common use.
RLG is based on the Sagnac effect, discovered in 1913 by French physicist Georges Sagnac. A beam of light is split in two and the two beams are made to follow a ring trajectory in opposite directions. On return to the point of entry, an interference pattern between the two beams is obtained. Applying a rotation to the apparatus induces a small difference between the time it takes light to traverse the ring in the two opposite directions. This introduces a tiny modification of the interference fringes. So the position of the interference fringes is a direct measurement of the angular velocity of the apparatus.

-Fiber-Optic Gyroscopes (FOG)
FOG leveraged the development of RLG and telecommunications optical fiber in the 1970s. Also based on the Sagnac effect, the FOG defines its light path by a wound coil of optical fibers instead of RLG’s mirrors and optical cavity. A unique feature of the FOG is the ability to scale performance. For example, doubling the coil length (typically ranging from tens of meters up to several kilometers for the highest performance) will decrease ARW by a factor of 2. Another advantage of using a FOG is that there are no moving parts, which means there will be no friction and, therefore, no inherent drift.

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Although RLG and FOG both achieve very good performance, their large size and cost (typically greater than $2,000 per axis) are limiting factors for many applications.

-Micro-Electro-Mechanical Systems (MEMS)
MEMS gyroscopes were demonstrated initially on quartz in the early 1980s, for example by Systron Donner. But the use of quartz as a base material does limit the compatibility with integrated circuit batch technology, and therefore, the cost reduction. After some effort, Charles Stark Draper Laboratory was the first to demonstrate a working MEMS gyro on silicon in 1987. But it was only seven years later that performance suitable for automotive application was achieved. And it is only in 1998 that Robert Bosch GmbH (Germany) introduced the first silicon MEMS gyro for Electronic Stability Program (ESP) systems, a major milestone enabling the widespread use of gyros for automotive and then consumer applications in the 2000s.
Both silicon and quartz MEMS gyros use the Coriolis force. When a vibrating mass is rotated, the Coriolis force creates an additional vibration, orthogonal to the direction of the vibration and the angular vector, and proportional to the angular rate. This additional Coriolis-induced vibration can be measured by a variety of mechanisms; this measurement provides direct knowledge of the angular rate.

The first MEMS gyroscope (see following figure) consisted of two silicon proof mass plates suspended by folded beams and vibrating in-plane. The perpendicular motion induced by the Coriolis force was detected by changes in capacitance between the proof mass and the substrates.

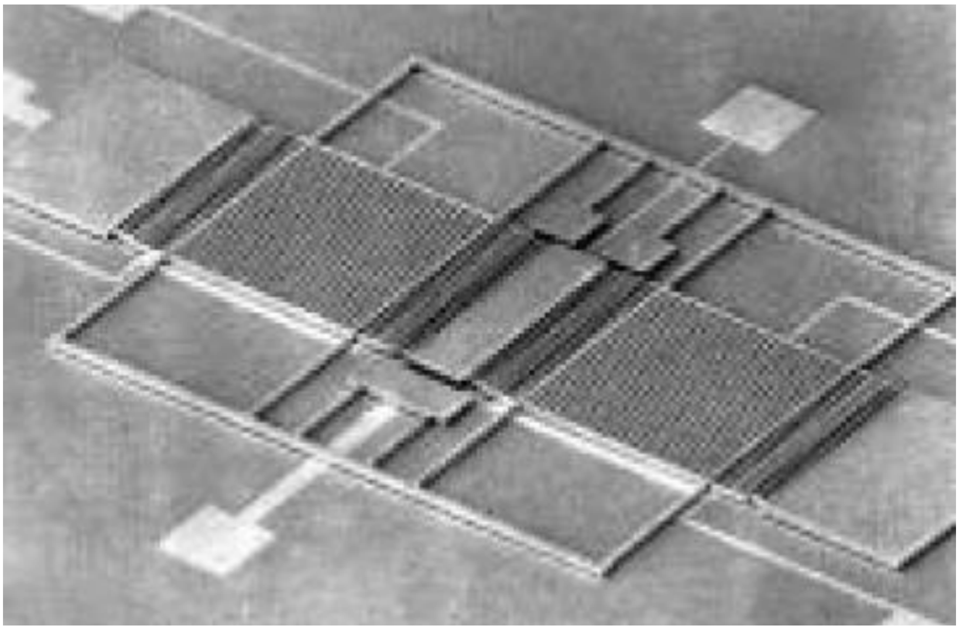

Figure 3: Top view of MEMS tuning fork gyro
(Courtesy of Draper Laboratory)

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As MEMS gyros are leveraging batch technologies initially developed for microelectronics, it is not surprising that they offer the most advantageous unit price among all gyro technologies. Apart from cost reduction, MEMS technology offers additional benefits such as size reduction, power reduction and ruggedness.

And what could be the impact of the rapidly growing consumer MEMS market on high performance MEMS gyros?

In the consumer market, the three-axis MEMS gyro is now the new standard, achieved with the combination of two in-plane (x- and y-axis) and one out-of-plane (z-axis) gyros on a single chip. The unit price of a consumer-grade 3-axis gyro is typically less than $2, a key requirement to be compatible with the bill of materials of the mobile phone industry. To satisfy this cost constraint, the design integration is achieved with very small proof masses that lead to poor bias stability. A typical consumer-grade gyro has a relative accuracy in the range of the percent rather than the ppm.

In the coming years, innovation in the consumer field is expected to come at the software level with data fusion. Therefore, the impact of the consumer products on high performance gyros is expected to remain very limited.

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Key gyro performance metrics

For the sake of simplicity, gyro precision is usually defined by a single parameter, namely its "bias stability" over the whole mission profile. This is the accuracy of the output of the sensor when there is no rotation applied. Ideally, bias stability should be equal to 0 but, in real measurements, there are always some errors created by the environment (thermal variations, vibrations, linear accelerations and others) or due to the sensor itself (misalignment, noise, aging, and others).

The main components contributing to the bias stability are presented in the following table. Best values obtained with MEMS gyros are also given according to latest publications and product releases.

Bias name	Description	Best MEMS gyro
Bias instability	**Allan variance method Room temperature No acceleration nor vibration**	**< 0.1 °/h**
Bias error with temperature	Over temperature range	5°/h
Bias error with vibration	Over vibration profile	
Bias error with acceleration	Over acceleration profile	
In-Run Bias stability	**Quadratic sum of previous errors Depending on mission profile**	**1 to 5°/h**
Offset	Initial Zero-rate output	30°/h
Shocks	Offset following high-g shocks	
Aging	Offset over years Based on lifetime model	
Run to Run Bias stability	**Quadratic sum of previous errors Depending on mission profile**	**5 to 30°/h**

Table 2: Bias instability, In-run and Run-to-Run bias stability

As a general comment, "bias stability" is usually several hundred times greater than "bias instability":

1) Bias instability is the best performance achievable with the gyro in a lab set-up,
2) Bias stability (in-run or run-to-run) is the real performance achieved during the mission. So the bias stability value strongly depends on each gyro mission profile. For some missions, it may be dominated by temperature errors, for others missions by aging.

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In conclusion, bias stability is the key parameter for most users. Unfortunately, bias stability cannot be summarized with a single figure within gyro specifications as its exact value will depend on the specific "use case" of each application.

The application grade is defined by the bias stability, as shown in the following table:

Application grade	**Bias stability**	**Relative accuracy (*)**	**Main application**
CONSUMER AND AUTOMOTIVE GYRO			
Consumer	10 °/s	3%	Motion interface
Automotive	1 °/s	0.3%	ESP
HIGH PERFORMANCE GYRO			
Low-end Tactical also called Industrial	10°/h (Earth rate)	10 ppm	Amunitions & rockets guidance
Tactical	1°/h	1 ppm	Platform stabilization
Short-term Navigation	0.1°/h	100 ppb	Missile navigation
Navigation	0.01°/h	10 ppb	Aeronautics navigation
Strategic	0.001°/h	1 ppb	Submarine navigation

Table 3: High performance gyro application-grade

(*) Relative accuracy is defined as the ratio between the bias stability to the measurement range, set here to +/- 300 degree per second for the sake of simplicity.

An interesting outcome of the previous table is that there is currently an "application gap" between automotive gyros and low-end tactical ones. Although automotive gyros suppliers have tried hard to leverage their existing gyros in mid-end applications, such as for platform stabilization, their success remains limited. There is currently no high volume application at this performance level.

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Gyro technologies comparison

It is always a tedious task to compare technologies, performances, and prices. Indeed, each technology is facing its own challenges and may cover a large range of performance depending on the exact application requirements. One approach is to look at the relative technology contribution for each application grade. In the following table, a technology with a relative contribution greater than 50% is called “REFERENCE”, respectively “CHALLENGER” for a contribution of 20 to 30%.

Gyro technology & application grade	DTG	RLG	FOG	MEMS
Low-end Tactical	-	-	-	REFERENCE
Tactical	Obsolete	Challenger	REFERENCE	Growing
Short-term Navigation	Obsolete	REFERENCE	Challenger	-
Navigation	-	REFERENCE	Challenger	-

Table 4: Leading technology per application grade
(Source: YOLE Développement, 2011 high-performance gyro market).

As explained previously, DTG is an obsolete technology that will continue to be replaced in the coming years.

RLG and FOG are mature technologies with similar performance and size. However, ongoing developments in solid-state optics and fiber technology may potentially lead to FOG with high performance in miniature designs. So RLG is expected to decline as it will be continually challenged by FOG.

MEMS technology has significant advantages, such as reduction of size, power and cost, and is the undisputed leader for low-end tactical applications. But the small size of MEMS gyros also creates challenges for attaining high performance. Currently, the bias stability of the best MEMS gyros is around 5 to 30 °/h. MEMS gyros have not yet fully reached the tactical grade, i.e. bias stability of 1 °/h, but have been getting much closer over the last few years. Experts agree that MEMS should be able to reach the tactical level in the near future, and then begin to challenge, and perhaps eventually oust, tactical RLGs and FOGs.

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MEMS gyro designs and performances

There are 3 main families of MEMS gyro designs, all relying on the Coriolis force. The following table summarizes the pros and cons of each design family:

Design family	Tuning fork	Vibrating Disk	Vibrating Ring
Rate axis	X, Y and Z	X and Y	Z
Sensitivity	GOOD	VERY GOOD	WEAK
Shocks & vibrations	GOOD	VERY GOOD	VERY GOOD
Bias stability	VERY GOOD	WEAK	MEDIUM

Table 5: Performance review of MEMS gyro design families.

The "Tuning fork" design family is dominant for high performance gyros and the most probable contender for tactical-grade MEMS gyro.

-Tuning Fork
Tuning fork is the dominant design family for high performance gyro. This design family is based on a pair of proof-masses (this type of gyro is also called dual-mass) that are electrostatically driven to oscillate with equal amplitude but in opposite directions. When the device is rotated, the Coriolis force creates an orthogonal vibration that can be sensed by capacitive electrodes. Many smart design configurations have been developed in order to minimize the mechanical coupling between drive and sense modes, to maximize the mechanical coupling between the two proof-masses, to optimize the parasitic vibration modes rejection…

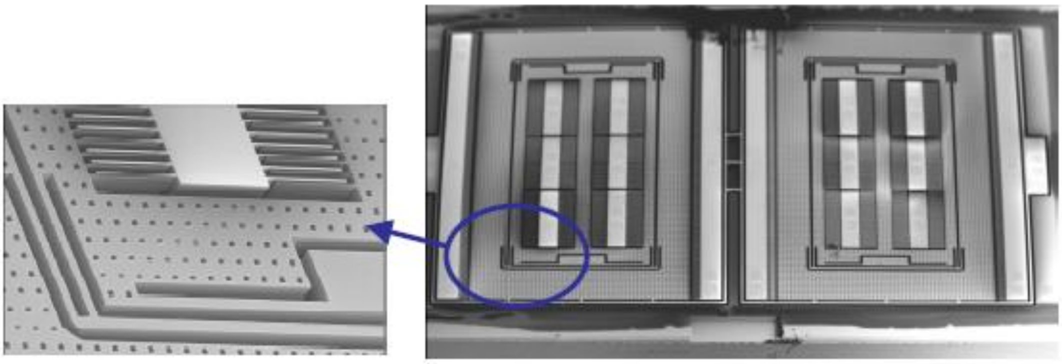

Figure 4: Tuning Fork MEMS die
(Courtesy of THALES Avionics, manufactured by TRONICS)

Tronics has manufactured several "tuning fork" MEMS gyros over the years. As an example, the gyro made for THALES Avionics has demonstrated a bias instability lower than 0.1°/h and a bias error with temperature of 8°/h, one of the best performance ever achieved with a MEMS gyro. More details can be found in the article "A New Silicon Tuning Fork Gyroscope for Aerospace Applications", B. CHAUMET et al, Symposium Gyro Technology 2009.

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-Vibrating Disk
The vibrating disk design family is based on a disk-shaped proof-mass that is driven to vibrate around its axis of symmetry. A rotation around an in-plane axis results in the disk tilting, a change that is detected with capacitive electrodes under the disk.

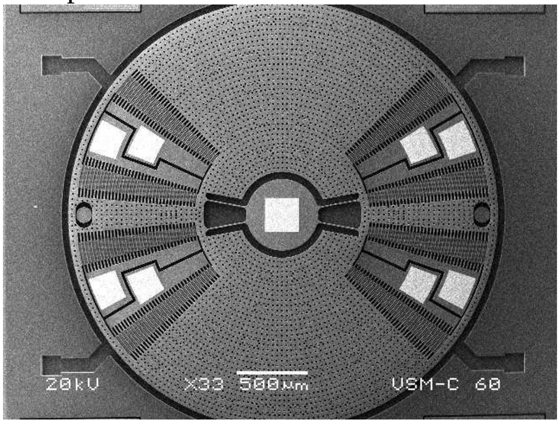

Figure 5: Vibrating Disk MEMS die
(Courtesy of Concern CSRI Elektropribor, manufactured by TRONICS)

The main advantage of these gyros is that they are inherently robust to linear acceleration and vibration (rotating disk motion, high frequency parasitic vibration modes of the disk). These gyros can also be easily adapted to sense two rotation axes at the same time using a single drive loop.

-Vibrating Ring
This design family consists of a ring-shaped silicon resonator which is supported internally by a set of beams. The ring is electrostatically vibrated by the drive electrodes into an in-plane, elliptically shaped, primary flexural mode. An angular rate about the z-axis (normal to the plane of the ring) excites the Coriolis force which causes energy to be transferred from the primary to the secondary flexural mode, 45 deg apart. The amplitude of the secondary mode can be detected by capacitive or piezo type measurement.

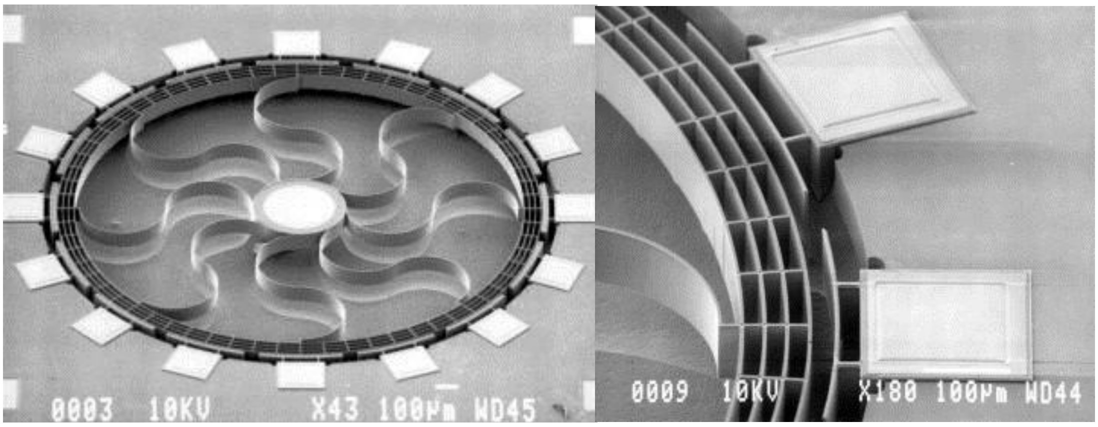

Figure 6: Ring MEMS die from Georgia Institute of Technology

Vibrating ring MEMS gyroscopes have a disadvantage in that the ring has a low vibrating mass and hence low sensitivity.

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MEMS gyro applications and supply chain

Applications for high performance MEMS gyros can be divided in two main categories:

-Replacement applications
In this category, MEMS gyros are replacing non-MEMS gyros (such as DTGs, FOGs and other mechanical gyros) due to their lower cost. For the buyer, the bill of materials reduction can be tremendous. Non-MEMS gyros typically cost a few thousand dollars, to be compared with a few hundred dollars for MEMS gyros. Thanks to this replacement, the cost reduction is typically greater than 80%. This is compelling motivation for a large set of system companies and it is currently fueling the growth and development of MEMS gyros. The vast majority of high performance gyros are used in inertial measurement units (IMUs) manufactured by vertically integrated companies such as Honeywell, Thales, Sagem, Goodrich, Northrop Grumman, and others.

-New applications
Due to their small size, MEMS gyros are also enabling new miniature high-performance inertial systems. Here are some examples of emerging applications:

1) Guided ammunition. The small size of MEMS gyros allows the introduction into applications previously considered out of reach, such as artillery shells or 30-mm bullets.
2) GPS-assistance applications for pedestrian navigation, such as tracking of first responder or soldier on a battle field. Indeed, a GPS signal is not always available (especially within buildings), can be easily jammed, and therefore might not be available in critical situations. This is why there is a need for inertial sensors that can complement a GPS signal without adding too much weight and volume.
3) Miniature unmanned land, air or marine vehicles. Inertial sensors are used for GPS assistance and also for camera or antenna stabilization.

Although many of these new applications will need time to fully penetrate the market, they are expected to require production of gyros in much larger quantities than replacement applications.

Supply chain
There are some unique considerations involved in producing MEMS gyros, as compared to other technologies such as DTGs or FOGs, including:

1) The MEMS device production infrastructure is very expensive. This is due to the cost of maintaining a clean room (chemicals, gases, power) together with the amortization of complex tools (such as DRIE) and the availability of highly qualified production team.
2) Unfortunately, having access to a good silicon manufacturing line is not enough. MEMS are highly sensitive to their environment, therefore extensive expertise in MEMS device packaging and calibration is also mandatory to achieve the best gyro performance.
3) Unit cost is dominated by fixed costs such as product development (NRE), tooling (mask set) and qualification. Indeed, thanks to batch manufacturing, there are typically several hundreds of MEMS dies on a single wafer. Low production cost can only be obtained for very large quantities, which are seldom achieved for high performance gyros.

MEMS gyro product offering

As explained above, large system makers control access to a large portion of the replacement market. This situation leads to two major consequences:

1) Large system makers do not have sufficient MEMS production volume to benefit from economies of scale. Their expensive MEMS production infrastructure is devoted to manufacturing small quantities of high performance MEMS gyro devices. This leads to high production costs. These high production costs, in turn, diminish the benefits of MEMS technology.

2) Large system makers are not interested in addressing a large set of applications outside their field. Thus, there are a large number of non-integrated companies that would be eager to integrate MEMS inertial sensors in their systems but are unable to do so.

So how can this “chicken and egg” issue be solved?

First, in order to achieve a competitive price for high performance gyro devices, it is mandatory to leverage an existing MEMS infrastructure.
As shown in the following figure, TRONICS has been active in the design and manufacturing of high performance MEMS inertial devices (accelerometers and gyros) for more than 10 years. High performance accelerometers and gyros are currently manufactured in France (Grenoble), where TRONICS has ample MEMS production front-end, back-end, testing and calibration capacity.

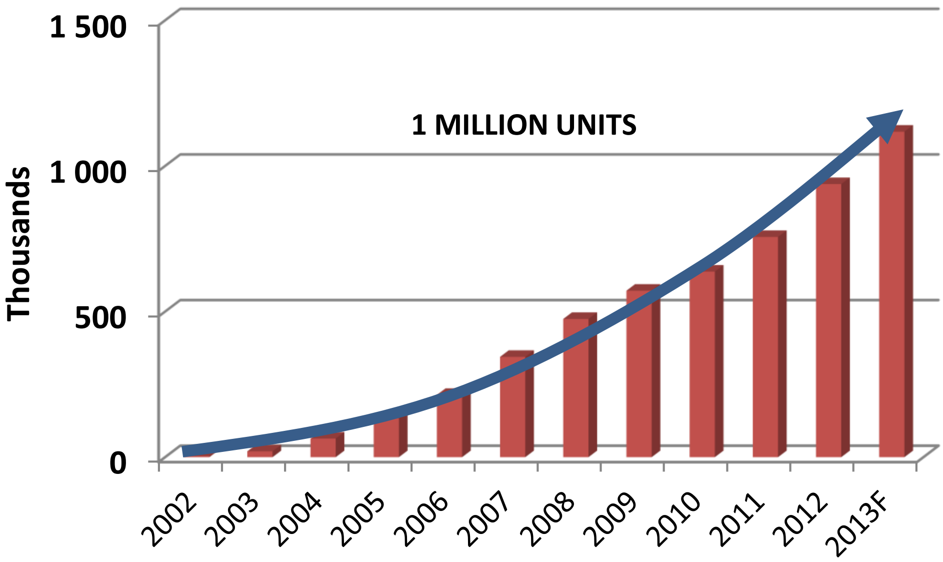

Figure 7: TRONICS’ cumulative production of high performance MEMS inertial sensors.

With a cumulative production of 1 million high performance inertial devices, TRONICS is bringing to its customers the benefits of a well-developed MEMS production infrastructure and the associated economies of scale.

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Secondly, it is mandatory to offer a standard product that has been designed to address a broad range of applications.

TRONICS now offers its own high performance gyro product, following requests from numerous customers over the years. The GYPRO2300 is a single Z-axis device, small (0.55 cm^3), lightweight (2.6 grams), and has a 24-bit output.

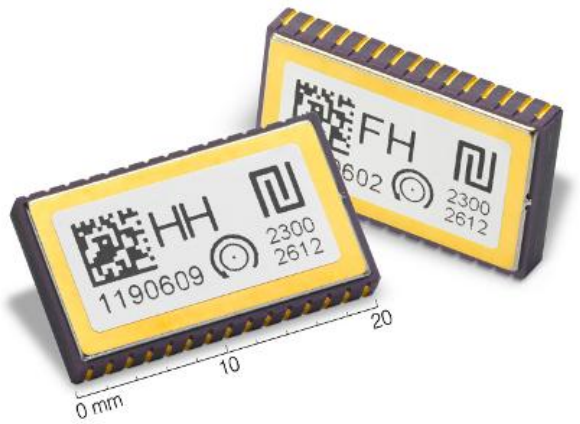

Figure 8: TRONICS GYPRO2300 high performance gyro.

This gyro was designed to meet the requirements of several applications, as shown on the following table:

Application	Key parameter	GYPRO2300 performance
Stabilization	Noise density	10°/h/√Hz
North seeking	Bias instability	1 degree per hour
Instrumentation	Bias error with temperature	+/- 0.05 degree per second

Table 6: Key parameter per application and performance of GYPRO2300

The GYPRO2300 is the first in a family of gyros that TRONICS intends to position at the forefront of MEMS based gyro performance.

Outlook for the next decade

Most of the current gyro technologies (DTG, RLG, FOG) have already reached a high maturity level, and no new gyro technology appears to be on the near horizon.

So what is next for the gyro designer?

Looking back over the last two decades, MEMS gyro performance has continually improved. Starting from the first functional MEMS gyro demonstrated in 1987, automotive-grade MEMS gyros were developed one decade later, and low-end tactical gyros in the following decade. It is clear that MEMS gyros still have the potential for an additional order-of-magnitude performance improvement over the next decade. This can be achieved by improving the precision of the micro-fabrication, reducing the sensitivity to packaging, and improving the electronics. Therefore, the next decade will likely be the one of the tactical-grade MEMS gyro.

The quest for MEMS gyro performance improvement to tactical grade and beyond will continue to dominate gyro developments in the coming years. With the launch of the GYPRO2300 gyro, TRONICS is at the forefront of the next chapter of the long history of gyro development.

ABOUT US:

TRONICS is an international, full service MEMS manufacturer with wafer fabs in Europe and the United States. TRONICS offers manufacturing services for a broad range of MEMS devices and delivers tested wafers, packaged dies or whole sensors, depending on customers' requirements. TRONICS' market share of the inertial MEMS foundry business reached 20% in 2011 (source YOLE Development).

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