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Excerpt
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1 Introduction

An inertial sensor is an observer who is caught within a completely shielded case and who is trying to determine the position changes of the case with respect to an outer inertial reference system.

Inertial sensors exploit inertial forces acting on an object to determine its dynamic behavior. The basic dynamic parameters are acceleration along some axis and the angular rate. External forces acting on a body cause an acceleration and/or a change of its orientation (angular position). The rate of change of the angular position is the angular velocity (angular rate). A speedometer is not an inertial sensor because it is able to measure a constant velocity of a body that is not exposed to inertial forces. An inertial sensor is unable to do so; however, if the initial conditions of the body are known, their evolution can be calculated by integrating the dynamic equation on the basis of the measured acceleration and rate signals.

In the overwhelming majority of practical applications, such as vibrational measurements, active suspension systems, crash-detection systems, alert systems, medical activity monitoring, safety systems in cars, and computer-game interfaces, the short-term dynamic changes of the object are of interest. But there are also many applications where inertial sensors are used for determination of the positions and orientations of a body, as in robotics, general machine control, and navigation. Owing to the necessity of integrating the corresponding dynamic equations, the accuracy requirements in these applications are usually higher because the measurement errors and instabilities of the sensors are accumulated over the integration time. Often inertial sensors are used in conjunction with other measurement systems, as in the case of robotics, where they are used together with position and force/torque sensors, or in the case of the integration of Inertial Navigation Systems (INS) with Global Positioning Systems (GPS) in cars. The accuracy of INS measurements can be improved significantly by correcting them with the GPS data using Kalman filtering procedures. The INS can then aid navigation even when the GPS is degraded or interrupted because of jamming or interference.

1.1 A short foray through the pre-MEMS history

The history of inertial sensors is relatively short. Despite the fundamental role played by inertial sensors in controlling the movement of a body, very little is known about early applications. This is even more remarkable given that most of the ingredients for building acceleration and angular-rate sensors, such as fine mechanics and precise spring technologies, were available from the late Middle Ages on and were used in the construction of, for instance, beautiful precision clocks.

Accelerometers

One of the most likely reasons for the late appearance of acceleration sensors (or “accelerometers” for short) was the lack of indicator technologies, or, in modern phrasing, the lack of interfaces. This is certainly the reason why some former applications of acceleration switches that needed only very simple mechanical interfaces can be found. An acceleration switch initiated an action at a certain level of acceleration, as in the activation of a detonator in some bombs during the First World War.

The first commercial accelerometer for broader application is credited to B. McCollum and O. S. Peters and was developed around 1920 [McCullom and Peters 1924]. It was based on a tension–compression resistance of a Wheatstone half-bridge where the resistances were formed by carbon rings. The next technological step was the use of strain-gauge transducers starting from around 1938, followed by the introduction of piezoelectric and piezoresistive transducers at the end of the 1940s. These transducers could capture the forces caused by the displacement of an elastically mounted mass within the sensor structure. Miniaturization and the high robustness of this type of sensor paved the way for broad applications in industry, terrestrial transport, aerospace, military uses, seismology, science, and so on. The piezoelectric and piezoresistive transducer principles were also among the first to be employed at the beginning of the entry into the world of inertial microelectromechanical systems (MEMS) – the world of the combination of micrometer- and nanometer-scale mechanical elements, sensors, actuators, and electronic circuits on one carrier or even on one chip. This entry was prepared in the late 1970s, for instance with the demonstration of a batch-fabricated silicon accelerometer with piezoresistive transducers. The silicon bulk micromachined proof mass was bonded between two glass wafers [Roylance and Angell 1979]. The commercialization of similar devices began around 10 years later and was very soon based on a variety of available transducer principles such as the sensing of capacitance changes between fixed and movable plates, the frequency measurement of resonant devices, the stabilization of a tunneling current by a closed-loop system, the sensing of thermal changes between a heater and a movable heat sink, and the sensing of changes of the thermal distribution within an air bubble. This broad invasion of new and old ideas in the world of microelectronic technologies has opened the way to inexpensive mass applications of inertial sensors in industry, cars, medicine, consumer goods, and so on.

Everybody knows the pioneering role of MEMS-based 50**g** accelerometers used in airbag ignition devices, which became the first high-volume product in the area of inertial MEMS. It was especially encouraging that within these successful high-volume products an example of the full monolithic integration of sensor and signal processing on one chip could be found. Analog Devices, supported by strong governmental funding, developed a special BiCMOS-MEMS process combining a known microelectronic process with a polysilicon deposition, etching, and release technology. Various inertial sensors were developed on the basis of this process, of which the first was the 50**g** accelerometer [Analog Devices 1993].

Gyroscopes

The stabilizing effect of rapidly rotating disks has been known for a long time and was used in ancient times for yo-yo-like toys and for ceremonies. Real angular-rate sensors emerged quite late but have had a remarkably long history compared with accelerometers. This obviously is due to the much lower early requirements on the speed of the interfaces and, of course, to the moderate values of the signals to be measured. For instance, the Earth's rotation is characterized by a rate signal of $360°/24$ hours or $0.1°/\mathrm{s}$.

The first technical realization of an angular-rate sensor took place around 1817 with the mechanical gyroscope designed by Johann Gottfried Friedrich von Bohnenberger in Tübingen in Germany. It was not a true sensor but a demonstrator of rotational effects.

The system was based on the spinning top and – not surprisingly – was used to demonstrate the mechanism of the Earth's axis' very slow precession accelerated in duration from a full cycle of 25 800 years to a small amount of seconds or minutes. Similar demonstrators were built around 1830 by the American Walter Johnson (Johnson's Rotascope).

The principle underlying the emergence of Coriolis forces within a rotating non-inertial coordinate system was demonstrated in 1851 by the French scientist Leon Foucault by building a 67-m-long pendulum with a mass of 28 kg within the Paris Pantheon (Fig. 1.1). This was the first real rotation sensor which measured the rotation of the Earth. Incidentally, a similar experiment was first performed in 1661 by the Italian physicist Vincenco Viviani and, after Foucault, implemented in countries all over the world. Under the influence of the Earth's rotation the oscillation plane of such a pendulum changes by $360° \sin\varphi$ in 24 hours. The angle φ is the geographic latitude of the experimental location. At the equator, the Foucault Pendulum does not show any reaction; at the poles, the rotation would be the full $360°/24$ hours. At all other places the tip of the pendulum will draw nice rosettes on the floor.

The Coriolis force was introduced by Gaspard-Gustave Coriolis, a French scientist, who described it in 1835. The Coriolis force appears in the equation of motion of an object in a rotating frame of reference and depends on the linear or angular velocity of the moving object. It will be considered in more detail in Chapter 8.

Using this principle, in 1852 Foucault built a spinning-top gyroscope ("*Meridiankreisel*"), which can be considered the basis of modern spinning-top gyros. The term "gyroscope" was introduced at this time ("gyros" – rotation, "skopein" – vision). However, the rise of rotation sensors was preceded by the use

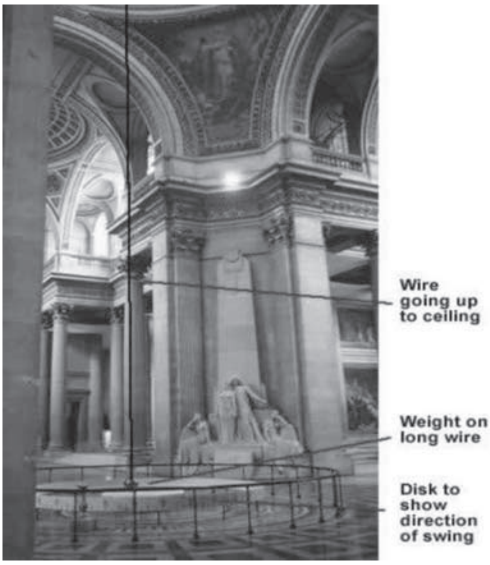

Figure 1.1 Foucault's Pendulum, in the Pantheon, Paris.

of the stabilizing ability of spinning wheels in torpedoes and cannon ammunition. Only in 1904 was the technical principle of the fast-spinning-top gyroscope patented by the German art historian Hermann Anschütz-Kämpfe [Schell 2005], who developed the idea of using the gyroscope within a compass (in 1908). The spinning wheel in a gyroscope is mounted on gimbals so that the wheel's axis is free to orient itself. The key element for a compass was the introduction of a mechanism that results in an applied torque whenever the compass' axis is not pointing North. The precession returns the compass' axis towards the true North if it is disturbed towards another orientation.

Other inventors such as the American Elmer Ambrose Sperry (1910) followed Anschütz-Kämpfe, and the acceptance of the gyro-compasses by the navy led to a quick penetration first on large ships and later on smaller ones and on airplanes.

Inertial navigation and platform stabilization in aircraft and naval vessels remained the domain of spinning-top gyroscopes for a very long time. Driven by the requirements for cost reduction and miniaturization, around 1960 new types of gyros like the vibrating-string gyro [Quick 1964], the tuning-fork gyro [Hunt and Hobbs 1964] and the vibrating-shell resonator emerged and opened the way to a drastic size and weight reduction, which finally ended with the transfer of these principles into the world of MEMS. The vibrating-string principle is based on the action of the Coriolis force on a simple oscillator such as a mass on a string or a vibrating beam; the tuning-fork principle is based on balanced oscillators; and the vibrating shell uses the two vibration modes of a ring or a cylinder as in the classic wineglass effect. These principles will be presented in Chapter 8.

The new miniaturized vibrating gyros captured marked shares of the market step by step. However, for high-precision applications a rival for the classical gyros emerged around the end of the 1970s: the optical gyroscope. These gyros based on optical ring resonators and later on fiber optics have dominated, for instance, the aircraft navigator market since 1980.

The transition from miniaturized gyros to the MEMS gyros was smooth. In miniaturized gyros it has become more and more difficult to realize bearings for endlessly rotating objects. The same problem applies for the early MEMS technologies and – with respect to specific friction, wear, and reliability – is still present today despite all the progress in this area. Only in 2008 did the first rotating MEMS gyro, developed by the Japanese company Tokimec, emerge on the market. Previous MEMS gyros used not the spinning-top principle, but rather the vibration or oscillation of masses within small linear or angular intervals as prepared by the miniaturized mechanical constructions. These so-called Coriolis vibratory gyroscopes (CVGs) – irrespective of whether or not they are based on MEMS – use at least two vibration modes of the structure, in which the Coriolis force excited by the interaction of the external rotation with the so-called primary mode causes an energy transfer to the secondary vibration mode. The vibrating elements are joined to hinges or anchors via springs. Such springs can be outstandingly formed in silicon because silicon possesses not only excellent mechanical and thermal properties in comparison with classical metals but also outstanding machinability.

However, the full implementation of a complete gyroscope structure by using only microelectronic or emerging MEMS technologies was not the first step towards MEMS-based gyroscopes. Instead the designers first tried to use MEMS technologies to create key components for miniaturized gyros, such as the quartz tuning forks with piezoelectric actuators and piezoresitive transducers developed by Systron Donner [Soderkvist 1990] and the silicon-based rings including the spring suspension for the vibrating-shell systems developed by British Aerospace System and Equipment [Hopkin 1997]. Such components were then mounted on appropriate carriers. Concurrently, typical MEMS-technology-based devices formed and bonded on wafer level were proposed around 1986 by the Charles Draper Laboratory [Greiff *et al.* 1991] and demonstrated first in 1991 with a bulk-micromachined tuning-fork gyroscope and a little bit later, in 1993, with a silicon-on-glass tuning-fork gyroscope [Weinberg *et al.* 1994]. In 1998, researchers at the University of Michigan demonstrated a polysilicon-ring gyroscope produced with a trench-refill technology [Ayazi and Najafi 1998]. Predecessors of different batch-fabricated gyros that used more exotic technology exist, but these designs could not prevail against products based on technologies that were becoming mainstream MEMS technologies. One of the most interesting of the non-mainstream products was the vibrating-ring gyroscope of the University of Michigan produced using metal electroforming of nickel into a thick polyimide mold on a silicon substrate, which was demonstrated in 1994 [Putty and Najafi 1994].

There were hundreds of different demonstrators from the University of Berkeley, from Samsung and Murata, from the Hahn-Schickard Gesellschaft–IMIT (Germany) and many others, but only a few were commercially successful. An excellent overview of the emerging MEMS-based inertial sensors can be found in Yazdi *et al.* [1998], which can be complemented by reading Shkel [2001].

1.2 Applications and market

The applications of the classical accelerometers are vibrometry, shock detection, tilt measurement, dynamometry, seismology and other areas related to test and evaluation of devices exposed to inertial forces. Some of these applications coincide with the main application areas of classical gyroscopes – inertial navigation and platform stabilization. MEMS technologies dramatically changed this relatively peaceful picture. Nearly every month a new application is created and checked for commercial attractiveness and realizability.

Some general trends

The trends of the inertial-MEMS market's development are not significantly different from those of the entire MEMS market if one excludes the two leading and very old and stable products – ink-jet heads for printers and write/read heads for magnetic and optical memory disks. These two market segments alone occupied around an estimated 25% of the about 10 Bn $ MEMS market in 2010. MEMS addressed very fragmented markets that have had predominantly low-volume and only a few large to truly high-volume applications. This market is transforming more and more into a high-volume market with steadily expanding size, and, crucially, with a growing number of different applications.

Compound annual growth rates (CAGRs) of 5% to 20% are typical for these different applications. At present the number of companies manufacturing MEMS products is around 270 in addition to 150 fab-less companies. Around 90 R&D industrial facilities, which are able to develop prototypes and to perform small-volume production, round off the picture of today's MEMS community. It should be borne in mind that in the 1990s three to five years were needed to develop new MEMS designs and five to eight years from the prototypes to volume production. In the case of safety-critical applications the time lapse was even longer. Now the overall time from design start to volume production has decreased by a factor of two to three and is reducing further. Consequently, the interest in research and development is enormous and is still growing. It will continue to grow as long as MEMS products penetrate all areas of human activity. Today the distance which has thus far been covered on the way to all-encompassing applications of MEMS and inertial sensors is almost negligible in comparison with the distance still to go.

The inertial-MEMS market

Within the MEMS market modern inertial sensors – accelerometers and gyros- have gained a considerable share, exceeding 20% of the expected 12 Bn $ MEMS market in 2011 (∼6 Bn $ in 2009). In 2005 nearly 80% of all applications were related to automotive safety functions such as automatic break systems (ABSs), airbag sensors, rollover sensors, electronic stabilization systems (ESP), and other anti-skid systems as well as to navigation. Starting with 50**g** accelerometers in airbag safety systems, the next step – the introduction of electronic stabilization control (ESC) by Bosch and Systron Donner in 1994 – was significantly accelerated by the disastrous elk test of the newly invented Mercedes-Benz A-Class in 1997. ESC had to rescue the reputation of the brand name of one of the leading makers of high-quality cars. In ESC, yaw-rate gyroscopes and low-**g** sensors are usually the decisive information sources for controlling the finely allotted brake forces on the different wheels to avoid accidents.

Rollover protection, highly sophisticated front and side airbags combined with safety-belt control, and suspension control, especially for trucks, and many other applications have not only expanded the market but also forced the development of new low-**g** accelerometers, of gyroscopes sensitive in different axes and with different accuracy levels, and – importantly – the co-integration of two or more sensors in one package or even on one chip.

Remarkably, the market shares of gyroscopes and accelerometers nearly equalized around 2005. New accelerometer applications mainly in the consumer market have shifted the relation to a stable 40% share of gyroscopes within the inertial-MEMS market. After 2012–13 the picture may change because the killer applications in the consumer market, which with an expected 1 Bn $ contribution will then be at least comparable in size to the other segments, have not yet been defined and are hard to predict.

Today, large companies are fighting for their share in the market of automotive inertial MEMS sensors. Among these, the world's largest MEMS-sensor manufacturer is Bosch in Germany, which has put considerable effort into the production of MEMS gyroscopes for automotive applications. However, British Aerospace Equipment Silicon Sensor Systems (BAE SSS), BEI Systron Donner, Delphi-Delco, Murata, Matsushita, and Samsung have also long been very successful and delivered many millions of gyros to component manufacturers in the car industry. Within the accelerometer market the Norwegian company Sensonor, with its 50**g** accelerometers, and the Swedish VTI Technolgies, which was long the leader in the low-**g** accelerometer market, have made surprisingly dominant contributions to the emerging killer applications within the automotive industry. However, the number of high-volume players in the inertial sensor market is quite limited, encompassing Bosch, Analog Devices, Freescale, and almost a dozen others.

Besides the automotive industry, the remainder of the market is dictated by consumer applications, which in recent years have shown dramatic growth, with CAGR 25%–30%. Accepted and growing applications are related to the use of inertial sensors in hand-held cameras for picture stabilization, in personal computers for hard-disk protection against mechanical shocks, in pedometers for motion sensing, and in more exotic products such as the two-wheel Human Transporter of Segway. Probably one of the most interesting applications is the motion sensing integrated into mobile phones, game controllers, toys and other human–machine interfaces. The Nintendo Wii's motion-sensing remote control has attracted the broad interest of the public to inertial MEMS. The consumer and information technology (IT) sector has increased from about 10% in 2005 to about a 45% share in 2009/10.

Within the consumer market the companies Analog Devices, Kionix, ST Microelectronics, and MEMSIC are the dominating players within the accelerometer business, while Panasonic and Murata have long led the gyro market. However, every year new companies are entering the market for inertial sensors, and the established manufacturers of inertial MEMS as well as newcomers are focusing their attention more and more on the consumer market. New systems such as very small and cheap one-axis sensors as well as more highly integrated multi-dimensional accelerometers and gyroscopes are now on the market. ST Microelectronics introduced in 2009 a three-axis high-performance gyroscope, whereas VTI announced a three-dimensional (3D) accelerometer combined with a 1D gyroscope [MEMSentry 2009]. Sensordynamics introduced in 2008 a combined one-axis accelerometer and one-axis gyroscope [Micronews 2009] and announced a three-axis accelerometer plus one-axis gyro combination. The race into the world of multi-axis inertial sensors, including completely integrated (six-axis) inertial measurement units (IMUs), is fully under way.

An IMU measures the accelerations and rotation rates on all three axes and, in principle, represents the (functionally) ultimate inertial sensor. Applications are numerous, ranging from medical 3D gesture and motion recognition via human–machine interfaces (HMIs) for game controllers and mobile phones to personal navigation systems.

The high-volume application of inertial MEMS in the automotive and consumer markets was for a long time in some contrast with aeronautic and defense applications. Here the high added value guaranteed a large benefit for the customer, and, consequently, the low quantities have been to some extent compensated for by good prices. Remarkably, within the last few years many inertial-MEMS products developed for the aeronautic and defense sector have reached commercialization. This sector has doubled within the last five years, approaching now around 50% of the size of the automotive segment.

As with aeronautics and defense markets, the industrial and medical segments of inertial MEMS' applications are also at the stage of entry to high-volume markets. Applications such as activity monitoring in pacemakers have considerable dissemination throughout the world. It can be expected that the inertial control of robots and machine parts with more than one degree of freedom (DOF) will achieve a quite broad distribution.

1.3 The ingredients of inertial MEMS

Inertial sensors convert the inertial forces caused by the input acceleration or rate signal into some physical changes such as deflection of masses or deviations of stresses, which then are captured by a corresponding transducer and transformed into an electrical signal. The electrical signal is subjected to some estimation procedures such as linear or nonlinear filtering in order to derive an estimate of the input signal. The final output represents the calibrated value of the measured acceleration or rate. Of course, not only electrical output signals are feasible; however, only in such exceptional cases as for instance in highly explosive environments are other forms of the output, such as optical signals, used. Within this book only sensors with electrical output signals are treated.

Accelerations and angular velocities are vectorial signals possessing absolute values and orientations. If only one component of the vector should be measured the sensor is denoted 1D or one-axis. If two or all three components of the acceleration or the rate signal should be captured, the sensor is called a 2D or 3D accelerometer, or a rate sensor.

Today a MEMS-based accelerometer or gyroscope is understood as a complete product that is packaged, calibrated, and tested, and has to be delivered to the customer, who wants to integrate this component with minimal effort into a higher-level measurement or control system. The level of accuracy required depends on the application. The environmental conditions for the integration of inertial MEMS at the customer site may be also quite different and usually are divided into classes with respect to the applicable temperature range and the exposure to humidity and aggressive chemicals as well as to vibration and shocks. The length of the lifetime, the reliability, and the safety against failures during operation may vary significantly, and to a large extent determine the product's price. Consequently, orders of magnitude may separate the complexity and the price of an inertial MEMS for different applications even if the underlying sensor principles are identical.

In order to make the following explanations and terminology systematic, it is meaningful to sketch a general structure of a sensor system with emphasis on inertial sensors. The system consists of not only the sensor itself but also additional components such as transducers and electronics. In Fig. 1.2 a very crude representation of the whole system is shown. The intrinsic sensor transforms the input signal – acceleration or rate – into a physical objective, which can be gathered by the transducer and transformed into an electrical signal. The sensor and transducer are subject to interactions with the package. In inertial MEMS the main interactions are stress and heat transfer. Environmental factors may be transferred via the package to the sensor and transducer, changing their behavior.

The electronic part consists of an input stage that amplifies the transformed signal into a conveniently manageable form. The electronics also may generate

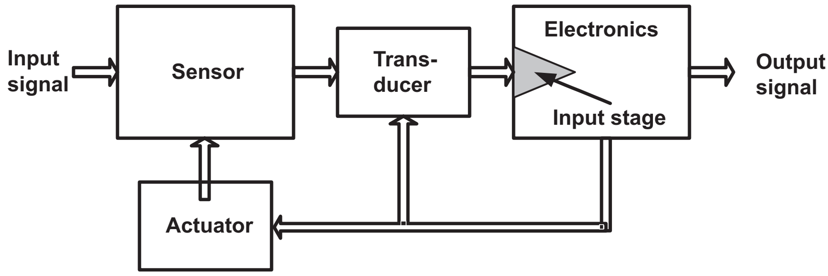

Figure 1.2 The general architecture of a sensor system.

excitation and control signals that are necessary for bias setting and for operational conditioning. Actuating stimuli may be used, for instance, for feedback control, as well as for test signals. In practice the borders between these generic blocks are quite fuzzy. The transducer and the electronic input stage often form an indivisible object where the input stage provides the necessary biasing and excitation for the transducer and, vice versa, parts of the input stage may act as components of the transducer. The transducer is often directly integrated into the intrinsic sensor. In general, the application of a certain transducer principle usually entails not only the choice of a certain transducer element but also the adaption of the sensor and the electronics.

Nevertheless, the generic structure shown allows us to systematize the understanding of the main interactions between the components.

- Feedback control is beneficial with respect to linearity and optimization of transfer characteristics. However, it requires actuators and, thus, additional effort. Therefore, not all sensors have feedback components and, where possible, sensors operate in an open-loop mode.
- The system performance is to a large extent determined by noise and disturbances. Typical noise sources exist within inertial MEMS. So, the intrinsic inertial sensor exhibits mechanical noise caused mainly by friction with the usually gaseous environment. For not-too-ambitious performance targets the dominant noise stems from the second noise source – the transducer and electronic stages, and here mainly from the electronic input stage.

In accord with the system structure illustrated, the various basic sensor principles, the transducer mechanisms, the corresponding governing models, and, last but not least, the typical error sources and performance parameters of the overall system will be covered by this book.

The seemingly central role of the sensor principle within inertial MEMS quickly dissolves when one looks at the many stages of creating the final product.

- A working environment for the sensor is usually established by the so-called zero-level packaging.
- The sensor signals must be acquired and processed.