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MEMS Inertial Sensors with Integral Rotation Means

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ABSTRACT

The state-of-the-art of inertial micro-sensors (gyroscopes and accelerometers) has advanced to the point where they are displacing the more traditional sensors in many size, power, and/or cost-sensitive applications. A factor limiting the range of application of inertial micro-sensors has been their relatively poor bias stability. The incorporation of an integral sensitive axis rotation capability would enable bias mitigation through proven techniques such as indexing, and foster the use of inertial micro-sensors in more accuracy-sensitive applications. Fabricating the integral rotation mechanism in MEMS technology would minimize the penalties associated with incorporation of this capability, and preserve the inherent advantages of inertial micro-sensors.

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1. Introduction

The rotation of inertial sensors is required for calibration, and in some cases, operation. Depending on the application, rotation may be limited or unlimited. The following is a brief history of rotation as applied to inertial sensors.

Indexing

An example of the application of limited rotation is indexing, in which, generally under static conditions, the sensor is rotated so that its input axis is pointed sequentially in each of two directions (at least), typically 180 degrees apart. Sum and difference of the two input signals, divided by two, provides a measure of sensor bias error and input respectively. The bias error may be recorded and removed from subsequent measurements. The use of indexing to measure and remove bias error is essential to the calibration of inertial sensors, including both acceleration and angle/angular rate sensors. Reference 1 outlines the basics of inertial sensor calibration.

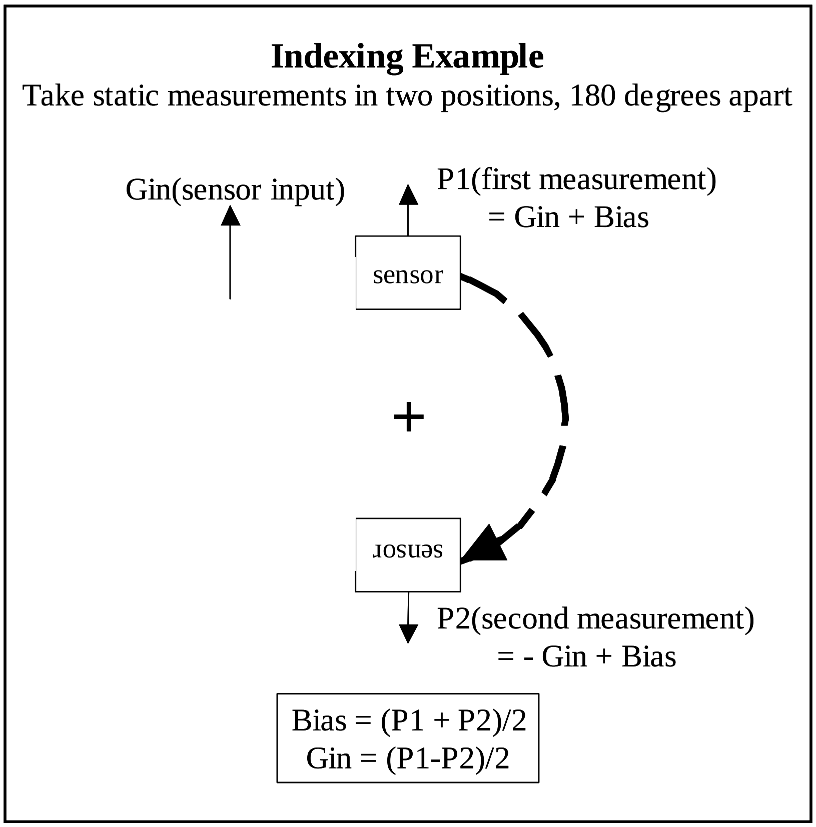

Figure 1: Example of Indexing to Measure/Remove Bias

Inertial systems sometimes incorporate an integral indexing capability for sensor bias measurement and removal during operation. This has the important benefit of eliminating day-to-day bias variations as an error contributor. Only the bias variation during the relatively short time between measurements is a factor. If, as is generally true, the short term bias variations are very much smaller than day-to-day variations, the performance improvement to be gained through indexing is substantial. An order of magnitude improvement is not unusual. It should be pointed out that indexing makes sense only if the magnitude of bias instability, of a gyro for instance, is about the same size as earth rate or smaller. If the bias is very large, say a hundred degrees/hour, most (~90%) of it can be measured by simply observing the bias under static conditions. This is the situation with some MEMS gyros. No indexing is required to measure and eliminate the effect of the great majority of the day-to-day bias changes. Also, short term bias variation is generally at least as large as earth rate. Therefore, even if day-to-day bias were totally eliminated through indexing, we would still have short term bias to deal with. In summary, the cost of incorporating an indexing capability in present-day MEMS inertial sensors would not be justified by the meager additional improvement in performance. This situation is expected to change soon, as discussed later in the report.

Indexing has been especially important in terrestrial application areas such as oil/gas well directional surveying, and land vehicle navigation, where indexing periodically during stationary conditions is possible. In most existing versions of these systems, the indexing mechanism consists of a "turntable" or gimbal which supports the entire inertial sensor assembly on bearings and includes a motor to rotate the gimbal to at least two angular positions. The mitigation of bias through indexing enables an accurate measurement of earth's rotation for north-finding (gyro-compassing) and earth's gravity for tilt measurement purposes. A specific example of limited inertial sensor rotation for indexing is described in Reference 2.

Carouselling

A possible application of either limited or unlimited rotation capability is in pointing the sensor input axis in a variety of directions during use so that the effects of bias errors tend to average out over a period of time. In the literature, this is sometimes referred to as "carouselling" or autocompensation (Reference 3). This form of bias mitigation has the advantage, unlike indexing, of being generally beneficial regardless of the size of the bias. A big disadvantage involves the necessity of dealing with data from a rotating coordinate frame. Reference 4 describes a wellbore surveying instrument which employs a cyclical (alternating ± 360 degrees) version of this technique. The systems of References 5, 6, and 7 use continuous, unidirectional rotation to achieve the same result.

Spin-Isolation

An example of the application of unlimited rotation is the spin-isolation of inertial angle/angular rate sensors (gyros). In rapidly spinning vehicles, it may be necessary to limit the sensor's rotation about its input axis, so that the sensor is not required to measure extremely large angular rates. Although the sensor is not rotating in inertial space, it is rotating relative to its case, which is spinning with the vehicle. Therefore, from a mechanism perspective, this is an example of unlimited rotation. References 8, 9, and 10 describe spin or roll-isolated inertial measurement systems for use in rapidly spinning aerospace vehicles. Reference 10 specifies the use of inertial micro-sensors. References 11 and 12 describe a spin-isolated wellbore inertial measurement system.

Figure 2 : The GLN-200, a Sandia-developed Spin-isolation System for the Northrop-Grumman LN-200 IMU

In a spin-isolation system, the sensor is be supported on a gimbal which provides the rotational degree of freedom which allows the sensor to remain relatively motionless, rotationally, while the vehicle spins around it. Relative to the limited rotation case, achieving an unlimited rotation capability requires the use of means such as slip rings to carry power and signals between the rotating and stationary elements of the gimbal. Similarly, a relative angle transducer is needed to keep track of the angular position of the sensor over 360 degrees of rotation. Obviously, the gimbal motor must also be capable of unlimited rotation operation. A concern for the roll-isolation gimbal and its components is angular rate capability. In some important applications, the relative angular velocity between the vehicle and the isolated sensor may reach several thousand degrees per second.

It should be obvious that an unlimited rotation capability has the advantages of both limited and unlimited capabilities. Reference 13 describes a wellbore inertial measurement system which has indexing as well as roll-isolation capability.

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2. Overview

Recently, the state of the art of inertial micro-sensors has advanced to the point where they are beginning to compete favorably with more traditional sensors, especially in size and/or cost-sensitive applications. An impediment to this advancement has been the relatively poor bias stability of inertial micro-sensors. These shortcomings are mitigated by the incorporation of an integral limited rotation capability that would enable indexing for bias mitigation and the use of inertial micro-sensors in more accuracy-sensitive applications. Similarly, the incorporation of an integral unlimited rotation capability for inertial micro-sensors would foster the use of micro-gyros in rapidly spinning vehicles.

An integral rotational capability carries a size and weight penalty which may range from a few percent for large systems to several hundred percent for small systems. This penalty can be reduced in some cases by the rotation of select sensors on an individual basis. In any case, fabricating the integral rotation mechanism in MEMS technology would assure that the penalty associated with incorporation of a rotational capability is minimized, and that the inherent advantages of inertial micro-sensors are maintained.

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3. Rationale For An Integral Rotation Capability For Inertial Micro-Sensors

<u>Indexing</u>

In the Introduction, it was pointed out that indexing, perhaps the simplest form of bias mitigation through rotation, would not have a big payoff with inertial micro-sensors which have been available in the past. (We'll return later to the question of the value of "carouselling".) This is because the bias variation which we seek to eliminate is generally at least as large, and frequently much larger than, earth rate (15 degrees/hr). Under these conditions, we can eliminate most of the bias simply by treating the entire signal obtained under static conditions as bias. The estimate will be in error by at most, earth rate, a small error on a relative basis.

However, more accurate MEMS IMUs have been introduced recently. For example, in initial lab testing at Sandia, a Honeywell HG1900 MEMS IMU has exhibited bias variability of less than 10 degrees/hr (1-sigma). Furthermore, even more accurate inertial micro-sensors may on the way. Figure 3 below (Ref. 14) illustrates a projection by Honeywell, Inc. that gyro bias variability of only a degree/hr may be achievable within a few years.

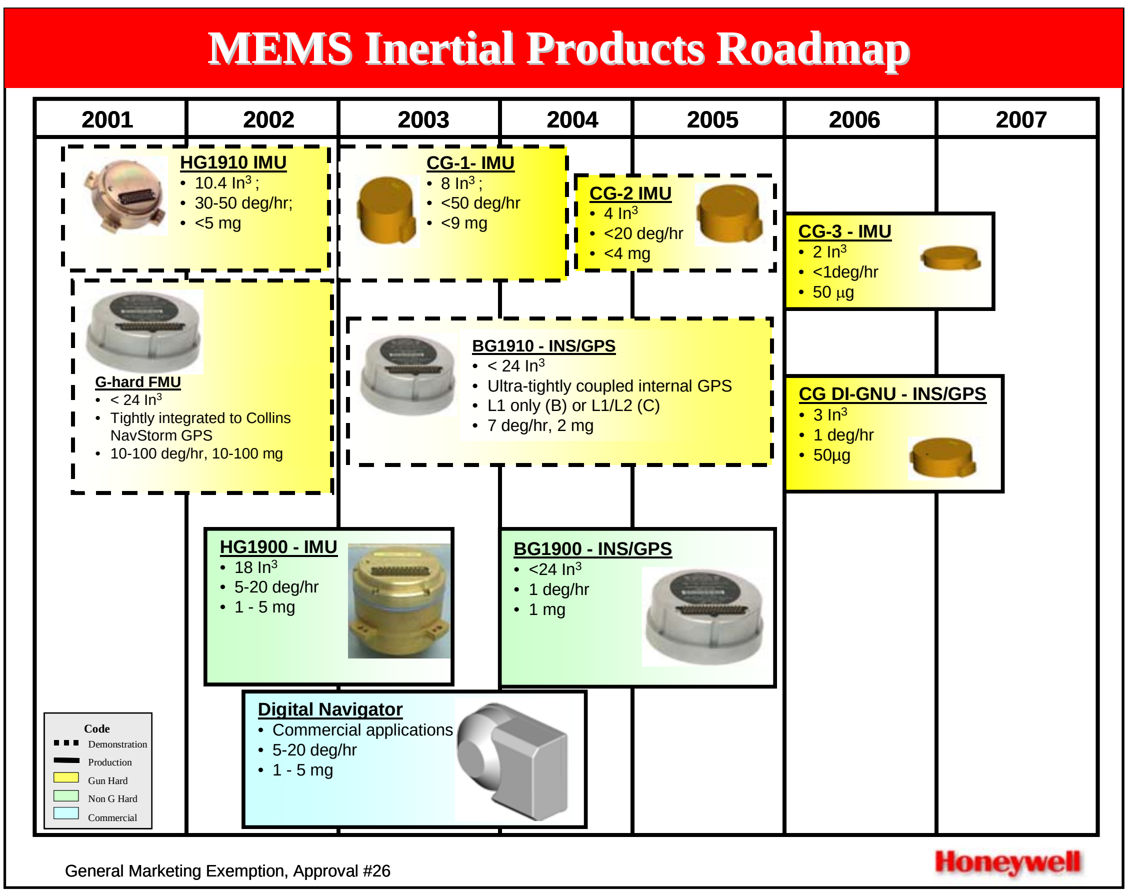

Figure 3: MEMS Inertial Products Roadmap, Honeywell, Inc. (Circa 2001)

If the efforts by Honeywell and others continue to bear fruit, then a parallel effort to develop a complimentary integral rotation capability for bias mitigation would be advantageous.

Carouselling

As previously mentioned, indexing involves the taking of data at two or more known angular positions under static conditions. The resulting bias measurement may be used to correct the data. In carouselling, which may be performed under dynamic conditions, the sensor input axis is rotated systematically to point in a variety of directions so that the bias tends to average out. Obviously, there is the matter of keeping track of this direction. Error in knowledge of the direction introduces error into the measurement. In some cases it may be necessary to utilize two sensors so that measurements along any input axis may be made by one sensor, as the other is being rotated to point along another direction. Figure 4 shows the simulated effect on HG1910 gyro data of rotating the input axis 180 degrees every minute. As can be seen, the direction of drift will be periodically reversed by this process, so that the growth of the drift angle in any one direction is limited.

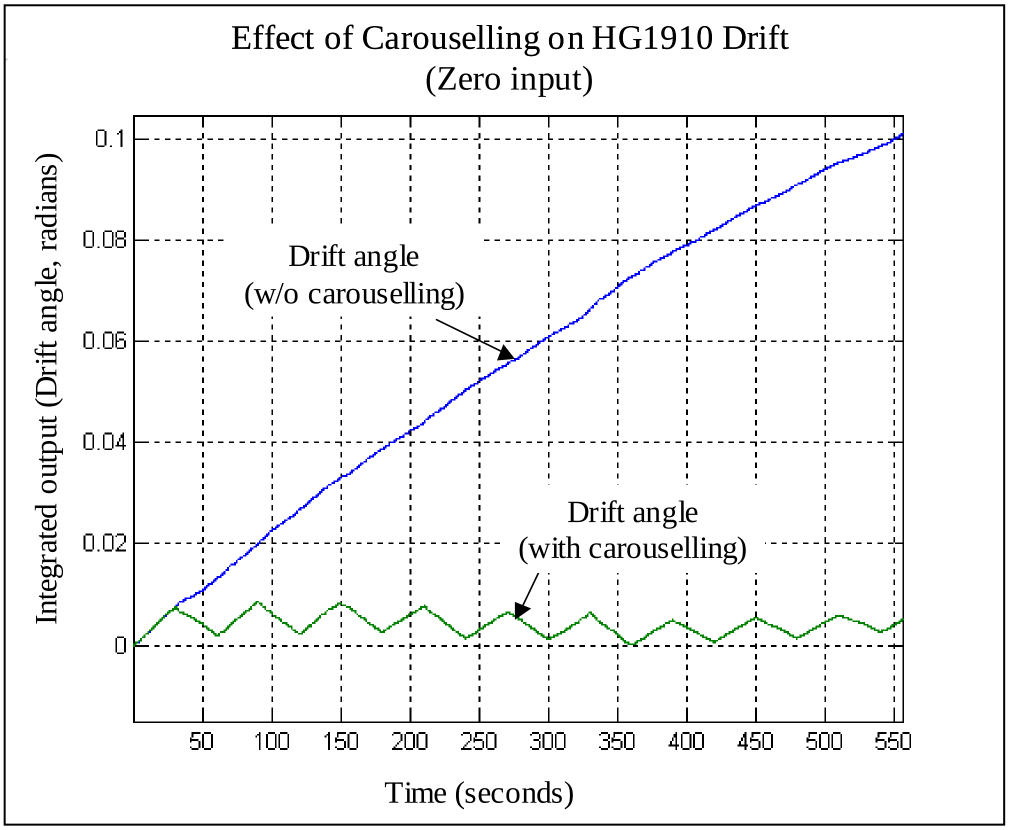

Figure 4: Effect of Carouselling on HG1910 Output

4. Design Concepts

In the apparatus discussed in this report, the micro-inertial sensor (gyro or accelerometer) would be supported by a MEMS rotation means or "turntable" so that it can be rotated in a controlled fashion. This rotation may be continuous or incremental. An example of a MEMS rotation means is illustrated in a Sandia patent, US Patent 6,313,562 (Ref. 15). Although maximum integration could probably be obtained by fabricating the rotation means in the same MEMS technology as the sensor, this is not necessary to the efficacy of the device. A device may consist of several MEMS elements which must be assembled into the complete device.

The rotation means may include mechanical means (stops) to limit rotation to specific angles. Alternatively, specific positions may be provided through the use of an integral angle transducer, or by keeping track of incremental changes of position as provided by an incremental drive mechanism as is described in US Patent 6,313,562.

MEMS Rotation Means
(Sandia Patent)

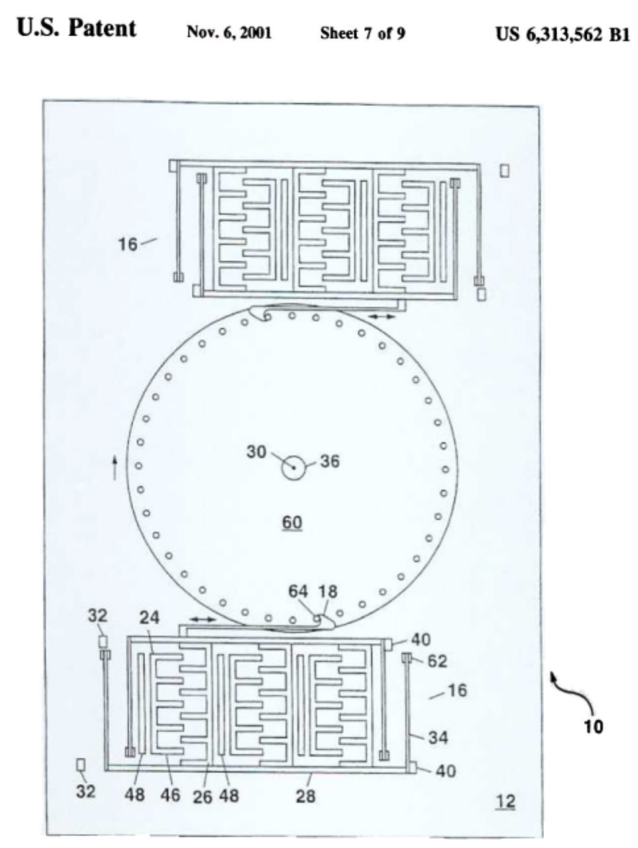

Figure 5: A MEMS Rotation Means

Figure 6 illustrates some of the salient features of a MEMS inertial sensor with integral MEMS rotation means.

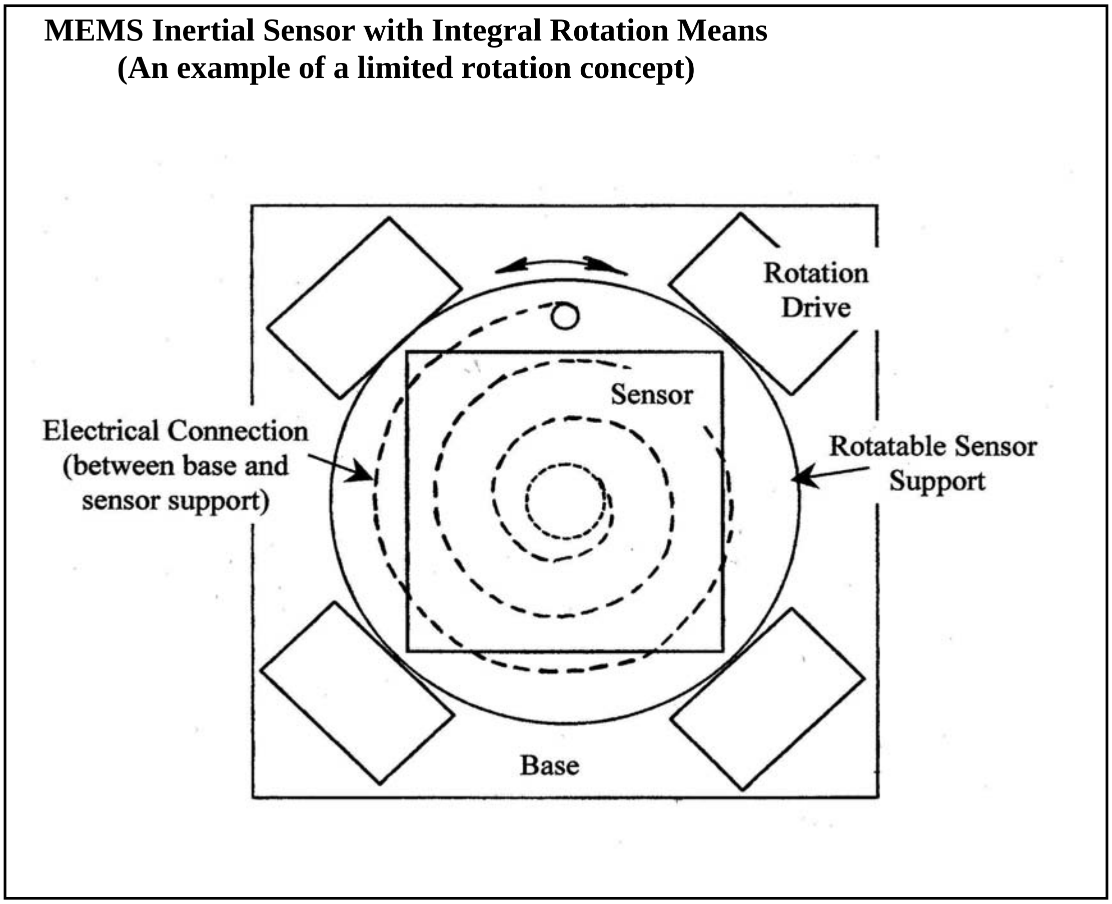

Figure 6: A Concept for a MEMS Inertial Sensor with Integral Rotation Means

Rotation may be about a sensor axis which is perpendicular to the sensor input axis or about the sensor input axis. In indexing, as discussed above, the rotation is about an axis which is perpendicular to the input axis. In the spin-isolation discussed previously, the rotation is about the sensor input axis.

It should be noted that the rotatable member may support more than one inertial sensor.

Electrical communication between the rotatable elements and the stationary elements may be accomplished by flexible members having electrically conductive paths, by sliding or rolling contacts, by RF (noncontacting) transmission, or by other means.

5. Conclusion

Requirements for very small size has led to the consideration of recently developed MEMS IMUs for many applications. However, the relatively poor bias performance of MEMS inertial sensors has been a stumbling block. In the past, bias mitigation through rotation has been applied successfully to a variety of inertial sensors. The preliminary results of studies at Sandia with MEMS IMUs indicate that proven rotational methods such as indexing and carouselling may be especially advantageous for MEMS sensors. The size penalty associated with incorporation of rotation means could be minimized through the use of MEMS fabrication processes. Sandia has extensive applicable experience in the fabrication of MEMS rotating devices. The development of a MEMS rotation means for MEMS inertial sensors would be of critical importance to the success of important programs at Sandia, including those involving reentry vehicle instrumentation and synthetic aperture radar (Ref. 16).

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