

CSDL-P-4127

**PROPOSED IEEE INERTIAL SYSTEMS
TERMINOLOGY STANDARD AND
OTHER INERTIAL SENSOR STANDARDS**

by

R. K. Curey (Northrop Grumman)

M. E. Ash (Draper)

L. O. Thielman (Honeywell)

C. H. Barker (Air Force)

February 2004

Presented at:

IEEE

Position Location Navigation Symposium 2004

Monterey, CA

26-29 April 2004

Proposed IEEE Inertial Systems Terminology Standard and Other Inertial Sensor Standards

Randall K. Curey, Northrop Grumman Navigation Systems Division, Wooland Hills, CA
Michael E. Ash, The Charles Stark Draper Laboratory, Inc., Cambridge, MA
Leroy O. Thielman, Honeywell International, Inc., Minneapolis, MN
Cleon H. Barker, 746th Test Squadron, Holloman AFB, NM

Abstract

A new inertial systems terminology standard is being developed by the IEEE/AESS Gyro and Accelerometer Panel for consideration by the IEEE Standards Board as IEEE Std 1559. It is intended to be a companion to IEEE Std 528-2001, IEEE Standard for Inertial Sensor Terminology. These two documents as well as IEEE standards that have been published for single- and two-degree-of-freedom spinning wheel gyros, laser gyros, interferometric fiber optic gyros, Coriolis vibratory gyros (including MEMS gyros), angular accelerometers, linear accelerometers, accelerometer centrifuge testing, and an inertial sensor test equipment and analysis document are discussed in this paper.

1. Introduction

1.1 Gyro and Accelerometer Panel Organization

For over 40 years, the Gyro and Accelerometer Panel of the IEEE Aerospace and Electronics Systems Society has been meeting bimonthly to develop inertial sensor standards, and recently inertial systems standards, that are published by the Standards Association of the Institute of Electrical and Electronic Engineers (see the bibliography at the end of this paper).

Bimonthly Panel meetings usually alternate on the East and West Coasts of the United States, with attendees from Japan, Korea, and Europe, as well as from the United States, representing many inertial sensor and systems producer and user companies. Meetings have also been held in Canada, France, Germany, and Russia.

The public Web site <http://grouper.ieee.org/groups/gap> contains information about the Gyro and Accelerometer Panel, including the Bylaws, future meeting locations and dates, application form for Panel or Information Only membership, and current Panel officers with e-mail addresses.

There is also a private Web page, accessible by Panel or Information Only members, that is password protected. It contains minutes of past meetings and drafts of documents under development. Panel members attend

meetings, where they discuss and vote on issues, as permitted by business commitments. Panel members who are also IEEE Standards Association members may participate in electronic ballots conducted by the IEEE Standards Association for affirming and reaffirming standards.

1.2 Standards Development Process

Any interested party may attend the open meetings where the standards are developed. The Panel and Committee meetings are conducted using Roberts Rules of Order. During a typical meeting, homework contributions to the standards are discussed and when appropriate a vote is held to determine if the new material is added to the document being developed. Consensus is sought in the standards development.

Before the Gyro and Accelerometer Panel can commence work on a proposed standard, a Project Authorization Request (PAR) describing the scope and purpose of the standard must be approved by the IEEE Standards Board, and a project number assigned.

Work on standards takes place in the full Panel meeting or in a subcommittee meeting, such as in the Panel's Gyro Committee or Accelerometer Committee, depending on the type of standard.

After development work is completed and approved by the full Panel, a proposed standard goes out for industry survey to determine possible additional revisions. An electronic ballot is then conducted by the IEEE Standards Association that requires 75% affirmative votes. Negative ballots require an attempt at issue resolution. A balance is required between the producer, user, and general interest ballot categories. Once approved by electronic ballot, the proposed standard is considered by the IEEE Standards Board for publication as an IEEE standard.

1.3 Proposed Inertial Systems Terminology Standard

The Gyro and Accelerometer Panel will soon be sending out for industry survey the newly developed Standard for Inertial Systems Terminology, document P1559.

This document has been under development for the past five years, and is proposed to be IEEE Std 1559 [14] as a companion to IEEE Std 528-2001, IEEE Standard for Inertial Sensor Terminology [4]. When approved by Panel Ballot and by the IEEE Standards Board, it will join the collection of IEEE inertial sensor standards that have previously been developed by the Gyro and Accelerometer Panel [1-12].

P1559 lists the inertial systems definitions in alphabetical order and educates about inertial systems as the chain of definitions is followed one to another. The chain of inertial systems definitions goes from inertial sensor assembly (ISA) containing accelerometers and/or gyroscopes, to inertial measurement unit (IMU) for navigation measurements and inertial reference unit (IRU) for attitude measurements, to inertial navigation system (INS) for accomplishing the navigation solution.

An INS can be gimballed or strapdown. A gimballed INS can be inertially oriented, local-leveled, indexed, carouselled, rate-biased, or thrust following. External aiding might be available, such as altimeters, depth meters, odometers, speed indicators, terrain or map matching, star sightings, radio navigation signals, etc. The advantages and computation methods of the various system mechanizations are described, including the use of quaternions in strapdown navigation algorithms. The various methods of INS calibration, initialization, alignment (gyrocompass, in-flight alignment), and transfer of alignment (velocity matching, optical) are described.

The coordinate frames, time systems, and gravitation models useful in inertial and radio navigation are defined. Lambert, proportional, and other guidance algorithms are described. Control moment gyros, reaction wheels, and momentum wheels, which are used for satellite attitude control, are also described.

1.4 Published Inertial Sensor Standards

Appendix A of this paper describes the standards that have been published for inertial sensor terminology, single- and two-degree-of-freedom spinning wheel gyros, laser gyros, interferometric fiber optic gyros, Coriolis vibratory gyros (including MEMS gyros), angular accelerometers, linear accelerometers, and accelerometer centrifuge testing.

1.5 Other Standards Under Development

Appendix B describes an inertial sensor test equipment and analysis document that is currently under development [13].

Standards that industry might want to develop for radio navigation aided inertial navigation systems (e.g. GPS/INS) could profitably make use of the IEEE standards development and publishing facilities that are available to the Gyro and Accelerometer Panel.

1.6 Bibliography of Inertial Sensor Standards

A bibliography of IEEE inertial sensor standards is given at the end of this paper, with publication dates ranging from 1969 to the present. Every 5 years, by vote of the Gyro and Accelerometer Panel, each of these IEEE standards is reaffirmed, updated, or withdrawn as a standard.

2. Types of Inertial Systems

An inertial system could be unaided, in which case it could suffer unbounded error growth with time. Hence, an inertial system often has external aids (see Section 7).

An inertial sensor assembly (ISA) is a structure containing multiple inertial sensors (gyroscopes and/or accelerometers) in fixed orientations relative to one another.

An attitude and heading reference system (AHRS) estimates the body angles of a vehicle with respect to the local level coordinate system, so it needs a leveling system, which could involve accelerometers. It needs gyros to maintain the north direction without an external reference, such as a magnetic compass or landmark sighting.

An inertial reference unit (IRU), such as for satellite applications, measures inertial angular motion in three dimensions without external reference. The sensors used are usually gyroscopes. External aids could be employed, such as sun, earth, or star sensors. Satellite attitude control could make use of momentum wheels, reaction wheels, or control moment gyros, as well as thrusters or earth magnetic field torquing.

An inertial measurement unit (IMU) measures linear and angular motion in three dimensions without external reference. The outputs of an IMU are incremental angles and velocities in the ISA frame. If the IMU includes gimbals, the gimbal angles are also output.

An inertial navigation system (INS) estimates a vehicle's position, attitude, and velocity as a function of time in a specified navigation frame using the outputs of an IMU, a reference clock, and a model of the gravitational field. A strapdown INS has the ISA fixed relative to the vehicle body, whereas a gimballed INS allows inertially-oriented, local-leveled, indexed,

caroused, rate biased, or thrust-following mechanizations.

An inertially oriented ISA is kept fixed relative to inertial space (i.e. relative to distant star directions), except for gyro drift, by servoing the gimbal motors to the gyro outputs. Local level platform control keeps the ISA aligned with a local level coordinate frame, such as with one axis aligned with the geodetic vertical and with a horizontal axis aligned relative to the north direction.

Carouseling involves continuous rotation of an ISA about one or more axes to reduce navigation errors due to gyro and accelerometer bias errors. To obtain perfect cancellation of constant bias errors, the carouseling should be about two orthogonal axes in inertial space. Periodic reversal of the sense of rotation reduces gyro scale factor wind-up errors introduced by the carouseling process.

Indexing is discrete rotation of an ISA about one or more axes to reduce navigation errors by estimating gyro and accelerometer error terms and/or reducing the effect of bias errors. Periodic reversal of the sense of indexing rotation reduces gyro scale factor wind-up errors introduced by the indexing process.

A rate biased ISA has a large rotation rate about an axis due to gimbal or vehicle rotation, in order to, e.g. prevent laser gyro lock-in. A thrust following ISA keeps one axis along the thrust vector of a vehicle, such as a missile, so that, e.g. a higher performing accelerometer could be along the thrust axis with lesser performing accelerometers along the cross axes.

An automotive navigation system can be implemented with fewer inertial degrees of freedom, typically just an azimuth gyro and perhaps accelerometers to detect if the automobile is on a hill, plus external aids, including global position system (GPS) radio navigation (whose signal can be lost in the urban canyon), speedometer/odometer, steering wheel angle, and map matching.

3. Components of an Inertial Navigation System

Figures 1 and 2 depict the components of strapdown and gimbale inertial navigation systems (INS). Besides the components described above, there are also power supplies (P/S), support electronics, shock/vibration isolation, thermal control, input/output (I/O) communications (including telemetry and test ports), a navigation computer, gimbal angle readouts (ARO), and gimbal torquers (TQR).

Not depicted is the system clock. Synchronization of the INS clock with clocks in other subsystems, such as in a GPS receiver, can be an important issue.

4. Calibration and Initialization

An inertial system requires calibration and initialization.

Calibration of inertial sensor biases, scale factors, input axis misalignments, and other parameters can be accomplished by discrete or continuous tumbles in the earth's gravity field about various axes, and by imparting angle rates about various axes. If the INS has gimbals, these calibrations can be done just prior to a mission by the INS itself.

A strapdown system would be provided with factory or depot calibrations from rate table testing that are partially updated prior to a mission by holding the INS stationary in a fixed orientation (zero velocity update, ZUP, also applicable to gimbale systems).

If a strapdown or gimbale INS is equipped with a GPS or other radio navigation external aid, the INS parameters could be calibrated during the first part of a mission by comparing the INS output with the GPS output, especially if the vehicle does maneuvers that excite INS error effects.

Some parameters require factory calibration for either a gimbale or strapdown system, such as temperature sensitivities, and nonlinear acceleration sensitivities that are calibrated on a vibrator or centrifuge.

The starting location of the INS must be specified as initialization information, either position alone if the INS is known to be stationary on the earth, or position and velocity if the INS is in a moving vehicle. The initialization information can be provided by the GPS in a GPS/INS.

An INS also requires alignment prior to a mission in order to determine its attitude and heading, unless this is accomplished in the first part of a mission in a GPS/INS by comparing INS and GPS outputs.

Alignment prior to a mission could use optical transfer of alignment from an external reference, or velocity matching of the accelerometer outputs in the given INS with the accelerometer outputs from a reference INS. Alternatively, if the INS is known to be stationary on the earth, its alignment relative to the local vertical can be determined by the accelerometers, and its alignment relative to the earth rotation vector determined by the gyros (a process called gyrocompassing), if the inertial sensors are accurate enough.

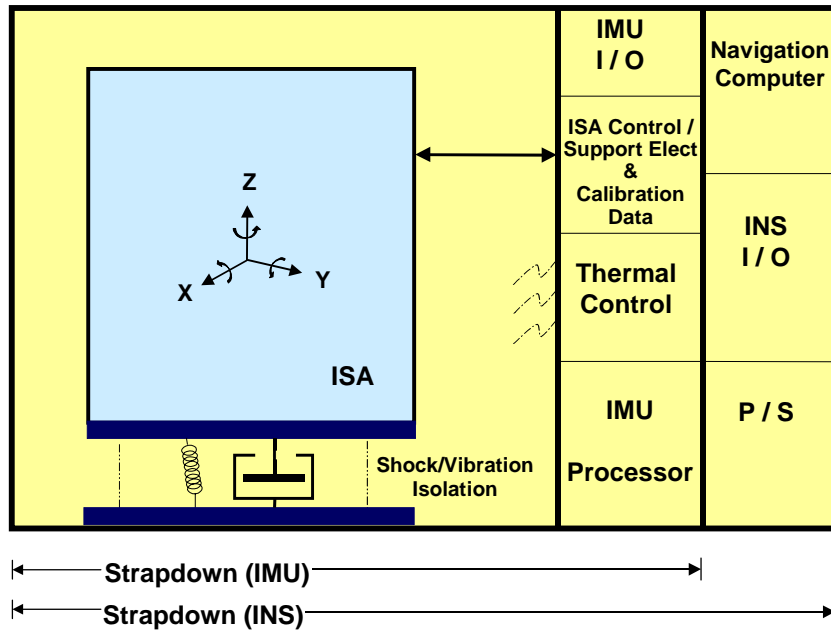


Figure 1—Strapdown inertial navigation system (INS)

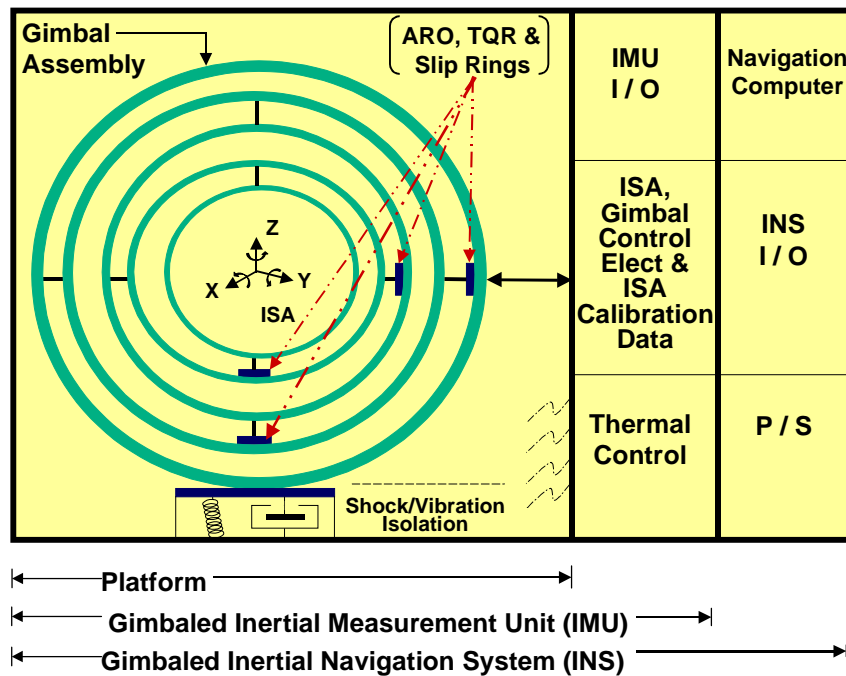


Figure 2—Gimbaled inertial navigation system (INS)

5. Kalman Filter and Other Estimators

Calibration and alignment require estimation of system and sensor model parameters when the system is provided with known inputs. Least squares maximum likelihood estimation can be employed in a self contained test, such as a tumble test, where no prior information is used. The Kalman filter is the preferred estimation technique when new information has to be mixed with prior information in sequential real time applications, such as updating previously calibrated parameters in a ZUP (Section 4) or updating parameters and navigation states using external aids (Section 7).

The states in a system, including model parameters (such as sensor biases, scale factors, and input axis misalignments) as well as the navigation states of position, velocity, and attitude, have initial values with defined covariances. The states and their covariances are propagated using the state dynamic equations, as explained in Section 6 for navigation states. Parameter state dynamic equations typically have right side zero plus dynamic noise.

When new measurements are available there is a Kalman filter update, where the updated state is the propagated state plus the Kalman filter gain matrix times the difference between the actual measurements and the predicted measurements using the propagated state. The Kalman filter gain matrix involves the covariances of the propagated states and the covariances of the measurements, in order to appropriately apportion the new information among the various states.

6. Inertial Navigation Computations

IMU accelerometer outputs are transformed from the ISA frame to a navigation frame using the gyroscope outputs with correction for centripetal and angular acceleration relative to the specified center of navigation. Navigation frames are typically inertial, earth fixed, or local level.

If the ISA frame is kept inertially oriented or local level, no angle transformation of accelerometer outputs is required for going to the preferred navigation frame. For a strapdown, caroueled or other such ISA, the attitude 4-vector quaternion Q can be propagated with the quaternion differential equation $dQ/dt = 0.5 Q\omega$, where quaternion multiplication is used, and where ω is the angular velocity 3-vector with real quaternion part zero in the ISA frame given by the gyro angle rate outputs. The transformation from the ISA frame to the navigation frame is calculated from Q using standard quaternion representation formulas.

In a strapdown, caroueled, or other such INS, the accelerometer transformation computation rate must be high enough (several hundred or thousand hertz) to prevent compensation errors for sculling and coning due to linear and angular vibration.

In the navigation frame the modeled gravitational acceleration is added to the accelerometer outputs, and the result numerically integrated to obtain the vehicle motion.

7. External Aids

Inertial navigation errors grow with time, but can be bounded by external aids.

Besides the errors arising from gyro and accelerometer error drift, there is a Schuler oscillatory error in inertially determined horizontal attitude or velocity arising from computing gravitational acceleration from inertially navigated computed position. It has an 84.4 minute period near the earth's surface.

There can be unbounded growth in vertical channel error, unless constrained by an external aid, such as an altimeter or depth meter. Water speed, air speed, ground speed (such as from a Doppler radar or after correction for water currents or wind), and speedometer/odometer readings are also important external aids. Star sightings, landmark sightings, and map matching are used as external aids.

The ultimate in external aid is provided by radio navigation system signals, such as from LORAN-C or GPS. A GPS/INS can make do with a lesser performing INS, where the precision long term navigation is done by GPS and the INS maintains attitude and propagates between low rate GPS navigation solutions and through GPS outages. Outages can be a serious problem in the urban canyon, and because of deliberate jamming.

Whenever an INS is informed that it has stopped moving, it can do a zero velocity update (ZUP), where it compares its output with the known fact that it is standing still on the earth or other celestial body, and adjusts its navigation solution and model parameters accordingly.

If an INS is informed that it is in free fall, it can calibrate its accelerometer biases and adjust its navigation solution accordingly.

8. Inertial Guidance

Guidance is generation of command signals for controlling vehicle motion and attitude to follow a

trajectory. Inertial guidance employs an aided or unaided inertial navigation system.

Lambert guidance commands a ballistic missile to follow the conic section trajectory in the $1/r^2$ gravitational field of the earth that goes between the launch and target points in a specified time. Terminal guidance uses sensors that give target information relative to the vehicle, often using the proportional guidance algorithm that gives thrust commands perpendicular to the missile-to-target line-of-sight that are proportional to the line-of-sight angle rate and closing velocity.

An autopilot is a system for autonomous control of a vehicle's attitude and/or velocity, typically accomplished using the outputs of rate or other high-bandwidth gyros and/or a speed indicator. Control of attitude and direction of motion (as in a ship or airplane) can accomplish dead-reckoning motion control.

Flight control is carrying out of guidance and autopilot commands.

Appendix A. Inertial Sensor Standards

A.1 Inertial Sensor Terminology

IEEE Std 528-2001 [4] gives definitions of terms related to inertial sensor technology, so they are not listed in the inertial systems terminology document P1559. IEEE Std 528-2001 has been translated into Japanese and published by the Japan Standards Association, with permission from the IEEE.

An inertial sensor is a position, attitude, or motion sensor whose references are completely internal, except possibly for initialization.

A gyro (gyroscope) is an inertial sensor that measures angular rotation with respect to inertial space about its input axis(es). The sensing of such motion could utilize the angular momentum of a spinning rotor, the Coriolis effect on a vibrating mass, or the Sagnac effect on counter-propagating light beams in a ring laser or an optical fiber coil.

A linear accelerometer is an inertial sensor that measures the component of translational acceleration minus the component of gravitational acceleration along its input axis(es). An output signal is produced from the motion of a proof mass relative to the case, or from the force or torque required to restore the proof mass to a null position relative to the case.

Details of the various types of inertial sensors and how to test them are given in the various standards developed by the Gyro and Accelerometer Panel.

A.2 Spinning Wheel Gyros

Older IEEE Stds 292-1969 [1], 293-1969 [2], 517-1974 [3], and 529-1980 [5] cover single degree of freedom rate and rate-integrating spinning-wheel gyros. One of the natural degrees of freedom of a spinning wheel is suppressed, and there is a pickoff for sensing the other degree of freedom. The pickoff output or the torque required to keep that pickoff at null is the measure of input angular rate, or there could be servo control of guidance system gimbals to keep the pickoffs at null for three orthogonal single-degree-of-freedom gyros.

IEEE Std 813-1988 [8] discusses two-degree-of-freedom dynamically-tuned gyros (DTG). The spinning wheel is on a shaft with a special hinge. At a certain tuned rotation rate, the spinning wheel becomes as if it has no attachment to the case. There is a certain amount of angular movement that is possible, e.g. about 0.5° , before the spinning wheel hits the gyro stops. Hence the pickoff of the angular displacement of the wheel relative to the case in two orthogonal directions X and Y perpendicular to the wheel spin direction can be used to servo-control guidance system gimbals, to keep the pickoffs at null and the platform on which the DTG is located fixed in inertial space along these axes.

Another method of operation is to use electromagnetic torquing about the X and Y axes to keep the pickoffs at null, with the amount of torque being the measure of the input angular rates about the X and Y directions. For a gimballed guidance system with two DTGs, one pickoff axis on one of the DTGs is caged (i. e., torqued to null) and the other DTG pickoff axes are kept at null with appropriate servo control of the guidance system gimbals.

A.3 Sagnac Effect Gyros

In a laser gyro (Std 647-1995 [6]), clockwise (CW) and counter-clockwise (CCW) propagation of laser light in a polygonal closed gas cavity (three, four, or more sides with mirrors at the vertices) leads to a standing wave(s). Under rotation of the gyro case, the standing wave(s) fixed in inertial space moves relative to a photodetector at one of the mirrors (Sagnac effect), which thereby provides a measure of the rotation as the wave crests move past the photodetector. The scale factor sensitivity (arcsec per laser wave crest pulse) is inversely proportional to the enclosed area of the closed laser path, so the larger the diameter or path length of the laser resonator cavity, the more sensitive is the laser gyro.

The laser gain medium is helium-neon gas with a high voltage discharge to excite atomic transitions. Piezo-optical or other path length control has to be provided. If operated near zero input angular rates, a technique for preventing lock between the CW and CCW laser beams is required; this can either be mechanical dither of the mounting post, or a magneto-optical means of shifting frequencies and creating multiple laser resonant frequencies.

A Fiber Optic Gyro multiplies the Sagnac effect scale factor by having many repeated turns of an optical fiber around a spindle, so that the longer the fiber length for a given enclosed area, the greater the sensitivity to detecting rotation. An Interferometric Fiber Optic Gyro (IFOG, Std 952-1997 [10]) sends clockwise (CW) and counterclockwise (CCW) laser light through the fiber. The interference pattern between the counterpropagating light waves after traversing the fiber is the measure of angular rotation for an open-loop IFOG. A closed-loop IFOG increases the dynamic range of the IFOG with an electro-optic ramping phase bias to keep the interference pattern biased $\pi/2$ radians in phase off null, with the ramp having to be reset every 2π radians of phase.

A.4 Coriolis Vibratory Gyros

The term Coriolis vibratory gyro (CVG) was invented by the Gyro and Accelerometer Panel to describe gyros based on the coupling of a structural, driven, vibrating mode into at least one other structural mode (pickoff) via Coriolis acceleration. These gyro types range from low-cost Micro-Electro-Mechanical-Systems (MEMS) devices on silicon or quartz chips to vibrating shell devices, such as the high-performance Hemispherical Resonator Gyro (HRG).

An informative annex in IEEE Std 1431-2004 [12] gives the principles of operation of these devices, whose dynamic model equations are similar to those of the Foucault pendulum, which can also be regarded as a CVG. Like the Foucault pendulum, there can be a quadrature motion to the desired vibratory motion that must be suppressed by a quadrature control loop in order to have a practical device.

Other control loops are for automatic gain control of the drive amplitude and vibration frequency control at the resonant natural frequency. The CVG is termed open-loop if the readout motion is monitored but not controlled, whereas it is termed force-rebalance if the readout motion is nulled. Another operating mode for a vibrating shell CVG is whole angle mode, where the change in the position of a standing wave pattern relative to the case is the measure of the change in inertial angle.

There are no rotating wheels in nature for detecting angular motion, although the flagella of certain bacteria can rotate continuously for locomotion. However, some insects use vibrating stubs or antennae attached to nerve endings to detect angular motion using Coriolis forces.

A.5 Angular Accelerometers

IEEE Std 671-1985 [7] discusses nongyroscopic angular accelerometers and other angular motion sensors. An example of such a device is a fluid filled torus or donut. When the toroidal case is rotated, the fluid tends to stand still. Paddles inserted in the fluid then detect that the fluid is moving relative to the case.

A biological example of such an angular accelerometer is provided by the three orthogonal semicircular canals in the vestibular system in the vertebrate (including human) inner ear, where hairs projecting into the fluid are attached to nerve endings. Also in the vertebrate inner ear are two IA orthogonal linear accelerometers (nearly horizontal when a person is standing) mechanized by calcium carbonate proof masses imbedded in a gelatinous material. Under acceleration or head tilt, displacements of the proof masses excite nerve endings.

A.6 Linear Accelerometers

IEEE Std 1293-1998 [11] provides a guide for specifying linear single-axis accelerometer performance and descriptions of tests for verifying this performance, both for general accelerometer characteristics and for specific types of accelerometers. Informative annexes describe specific types of nongyroscopic accelerometers, namely pendulous force-rebalance accelerometers, Vibrating Beam Accelerometers (VBA), and micromechanical accelerometers.

An accelerometer measures the difference between total acceleration and gravitational acceleration along its input axis(es) by the movement of a proof mass relative to the accelerometer case. Piezoelectric accelerometers, used to measure ac accelerations by the strain on a piezoelectric sensor attached to a proof mass, such as during vibration tests, are not discussed, nor are gyroscopic accelerometers or gravimeters (input-axis-vertical limited-range accelerometers) that have a narrow range of applications.

The pickoff for proof mass movement in a macro-sized force-rebalance accelerometer could be electromagnetic, capacitive, or optical. The forcer or torquer to restore the proof mass to the null position is usually electromagnetic. However, the restoring force for a

three-axis low-g accelerometer for space applications is capacitive.

A VBA has piezoelectrically-driven quartz resonators or electrostatically-driven silicon resonators attached to separate proof masses or to a common proof mass, where the measure of acceleration is the difference frequency of the IA-antiparallel resonators for common mode rejection of many error effects.

Micromechanical (MEMS) accelerometers are made from silicon or quartz chips using photolithographic and chemical etching techniques from the integrated circuit industry with pendulous or translational proof masses, and are thus low cost. They are often open loop devices, where the deflection of the proof mass against an elastic restraint measured capacitively, piezoresistively, or otherwise is the measure of acceleration. A MEMS accelerometer could be a force-rebalance design using a capacitive torquer or forcer.

IEEE Std 836-2001 [9] describes calibration of accelerometer higher order acceleration-sensitive model terms using a precision centrifuge. Overload capacity and other such tests can employ a lesser accuracy centrifuge.

Appendix B. Other Documents Under Development

Document P1554 [13], a recommended practice for carrying out gyroscope and accelerometer tests, will soon be completed. Inertial sensor test equipment and instrumentation is described, including test tables and fixtures, centrifuges and vibrators, environmental chambers, radiation test facilities, and general and sensor specific electronics, such as continuous counters, phase-locked loops, voltage-to-frequency converters, voltmeters and A/D converters, etc.

Data acquisition computers and software are described, including real-time digital filtering and automatic test equipment. Data analysis techniques are discussed, such as fitting models to data and performing Power Spectral Density (PSD) and Allan variance noise analyses.

The Gyro and Accelerometer Panel is also undertaking the revision of some older documents.

Acknowledgement

The members of the Gyro and Accelerometer Panel contributing to the proposed inertial systems terminology standard are too numerous to acknowledge individually. Special mention is made of Steven L. Saks of the Aerospace Corporation, who provided Figures 1 and 2 in this paper, and also in P1559.

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- [8] IEEE Std 813-1988 (R2000), IEEE Specification Format Guide and Test Procedure for Two-Degree-of-Freedom Dynamically Tuned Gyros
- [9] IEEE Std 836-2001, IEEE Recommended Practice for Precision Centrifuge Testing of Linear Accelerometers
- [10] IEEE Std 952-1997 (R2003), IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Interferometric Fiber Optic Gyros
- [11] IEEE Std 1293-1998 (R2003), IEEE Standard Specification Format Guide and Test Procedure for Linear, Single-Axis, Nongyroscopic Accelerometers
- [12] IEEE Std 1431-2004, IEEE Standard Specification Format Guide and Test Procedure for Coriolis Vibratory Gyros
- [13] In preparation, P1554, Recommended Practice for Inertial Sensor Test Equipment, Instrumentation, Data Acquisition, and Analysis
- [14] In preparation, P1559, Standard for Inertial Systems Terminology

Proposed IEEE Inertial Systems Terminology Standard and Other Inertial Sensor Standards

Randall K. Curey	Northrop Grumman NSD, Woodland Hills, CA
Dr. Michael E. Ash	The Charles Stark Draper Laboratory, Cambridge, MA
Leroy O. Thielman	Honeywell International, Minneapolis, MN
Cleon H. Barker	746th Test Squadron, Holloman AFB, NM

Presentation Outline

- Gyro and Accelerometer Panel (GAP) introduction
- Proposed Inertial Systems Terminology standard
- Published standards
- Other standards under development

Gyro and Accelerometer Panel Organization

- **Part of the IEEE Aerospace and Electronics Systems Society**
 - Panel in existence for over 40 years
 - Two committees (Gyro and Accelerometer)
 - Write and maintain inertial sensor and system standards
 - Members and information only
 - Yearly membership renewal required
- **Bimonthly panel meetings**
 - Usually alternate between East and West Coasts
 - Have also been held in Canada, France, Germany, and Russia
- **Next meeting is Thursday and Friday of this week**
- **Public web site for general information**
 - <http://grouper.ieee.org/groups/gap>
- **Private web site for sharing work in process**

Standards Development Process

- Any interested party may attend the open meetings where standards are developed
 - Work consists of real time efforts plus homework submittals
 - New additions and changes are discussed and voted upon
- Project authorization request (PAR)
 - Defines scope and purpose
 - Approved by IEEE Standards Association
- Work typically takes place within appropriate committee
- Work on terminology documents takes place in full panel meetings
- Proposed standards, once developed, are sent out for industry survey, then panel ballot (75% affirmative vote required)

Proposed Standard

- **P1559 “Standard for Inertial System Terminology”**
 - Over 5 years in development
 - Currently working on draft 21
 - Companion to IEEE Std 528 “IEEE Standard for Inertial Sensor Terminology”
- **Purpose**
 - Compile and standardize terminology used in the development, manufacture, test, and use of inertial systems
 - Serve as a basic reference for producers and users of inertial systems
- **Alphabetical order**
- **Cross linked definitions**

Types of Inertial Systems (1 of 3)

- **Inertial sensor assembly (ISA)**
 - A structure containing multiple inertial sensors in fixed orientations relative to one another
- **Inertially oriented**
 - ISA is kept fixed relative to inertial space (i.e. relative to distant star directions), except for gyro drift
- **Local level**
 - ISA is kept aligned with a local level coordinate frame
- **Rate biasing**
 - ISA has a large rotation rate about an axis due to gimbal or vehicle rotation, in order to, e.g. prevent laser gyro lock-in
- **Thrust following**
 - One axis of an ISA is kept along the thrust vector of a vehicle

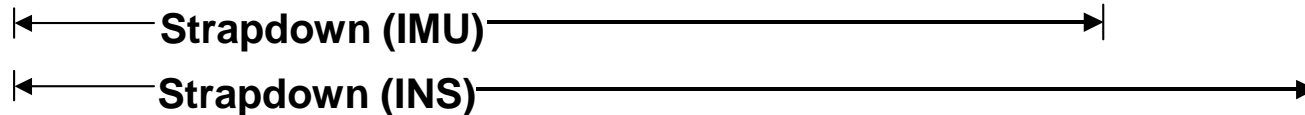
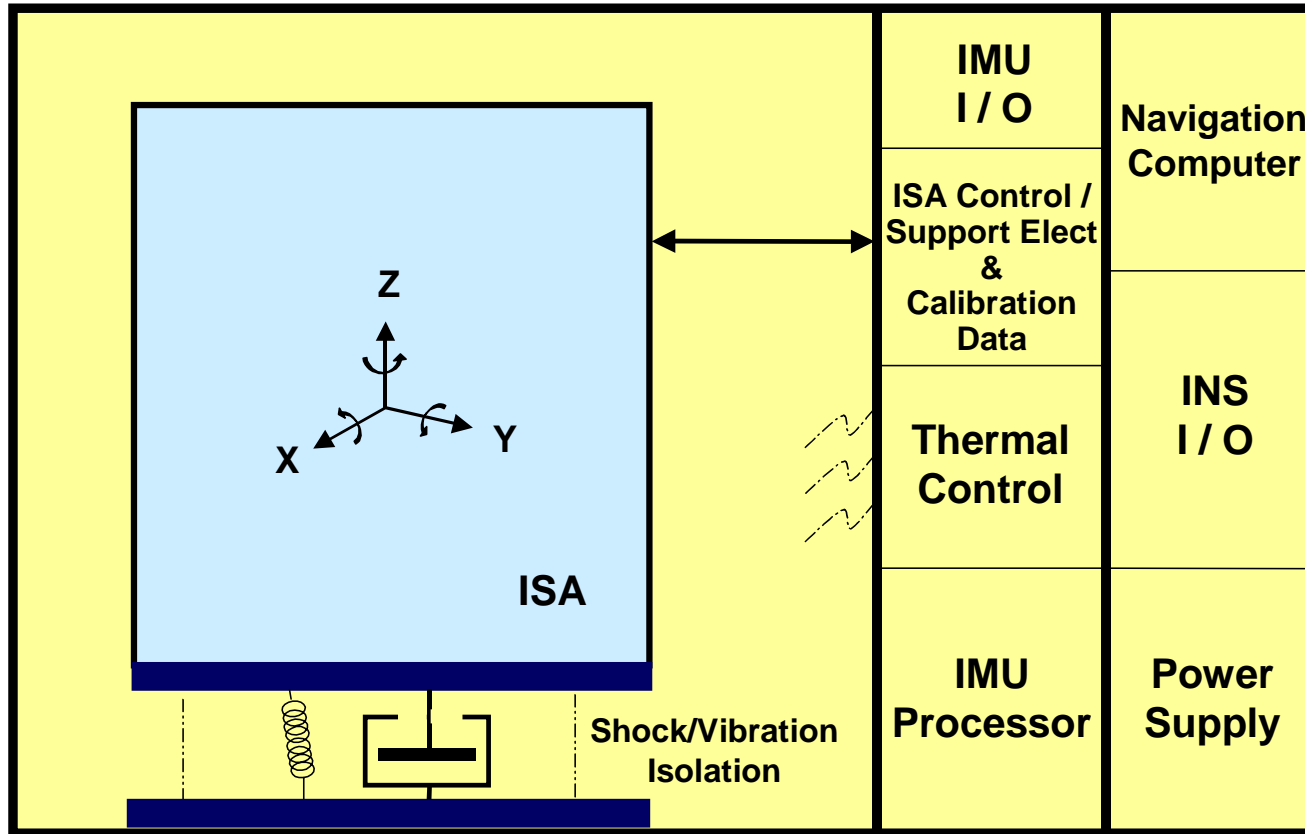
Types of Inertial Systems (2 of 3)

- **Attitude heading reference system (AHRS)**
 - Estimates the body angles of a vehicle with respect to the local level coordinate system
- **Inertial reference unit (IRU)**
 - Measures inertial angular motion in three dimensions without external reference
- **Inertial measurement unit (IMU)**
 - Measures linear and angular motion in three dimensions without external reference
- **Inertial navigation system (INS)**
 - Estimates a vehicle's position, attitude, and velocity as a function of time in a specified navigation frame
- **Automobile navigation system**
 - Can be implemented with fewer inertial degrees of freedom

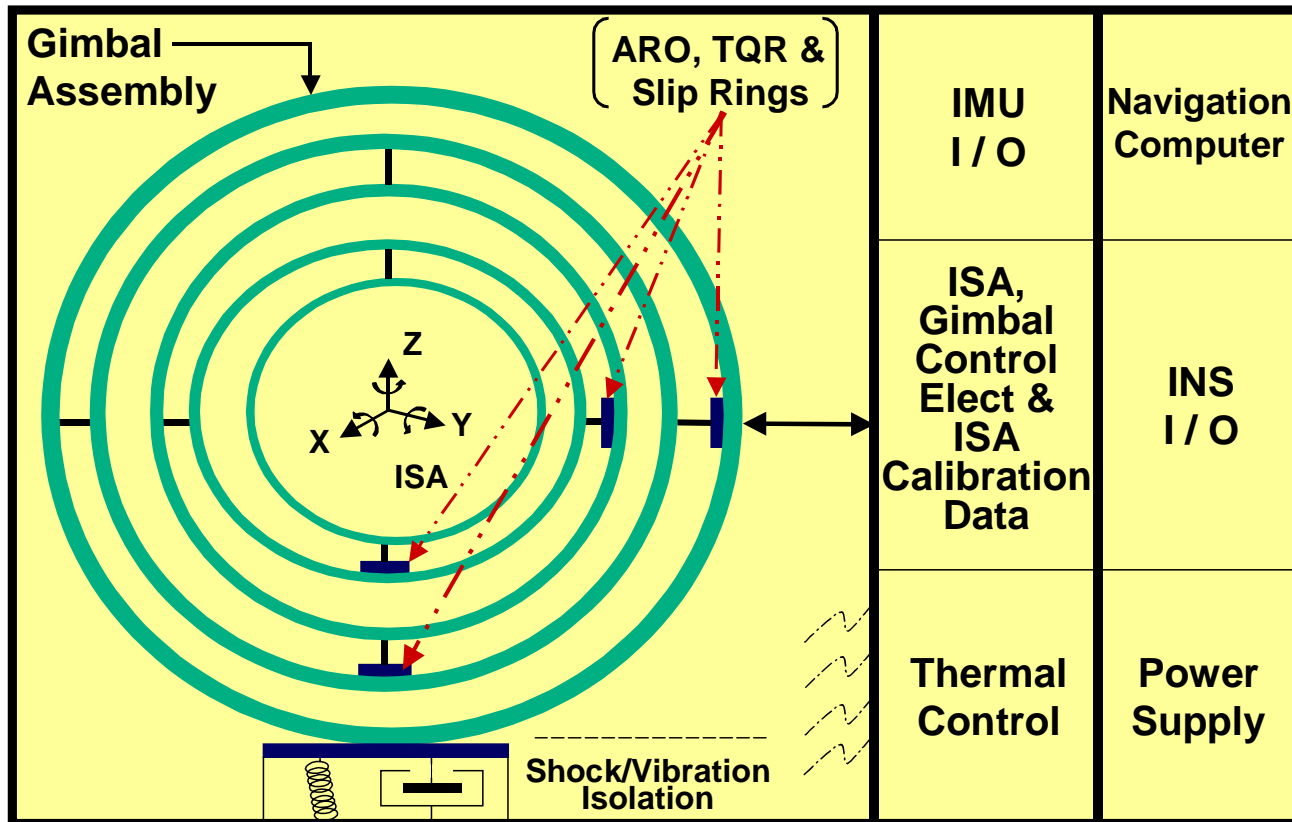
Types of Inertial Systems (3 of 3)

- **Strapdown INS**
 - Has the ISA fixed relative to the vehicle body
- **Gimbaled INS**
 - Allows rotation of the ISA for calibration and for orientation control during inertial navigation
- **Carouseling**
 - Continuous rotation of an ISA about one or more axes to reduce navigation errors due to gyro and accelerometer bias errors
- **Indexing**
 - Discrete rotation of an ISA about one or more axes to reduce navigation errors by estimating gyro and accelerometer error terms and/or reducing the effect of bias errors

Components of a Strapdown Inertial System



Components of a Gimbaled Inertial System



Calibration

- **What is calibrated**
 - Inertial sensor biases, scale factors, input axis misalignments, and other parameters
- **How is it accomplished**
 - By discrete or continuous tumbles in the earth's gravity field about various axes, and
 - By imparting angle rates about various axes
- **Factory or depot calibrations are required for various parameters**
 - Temperature sensitivities
 - Nonlinear acceleration sensitivities
- **Gimbals allow on-vehicle calibration**
- **GPS can be used to calibrate a system during the first part of a mission**

Initialization and Alignment

- **Starting location of the INS must be specified**
 - Position alone if the INS is known to be stationary
 - Position and velocity if the INS is in a moving vehicle
- **How provided**
 - From an external source, or
 - By the GPS in a GPS/INS
- **Alignment required to determine attitude and heading**
 - Prior to mission, or
 - In the first part of a mission in a GPS/INS
- **Alignment methods**
 - Gyrocompassing
 - Velocity matching
 - Optical transfer of alignment

Kalman Filter and Other Estimators

- Calibration and alignment require estimation of system and sensor model parameters
- Least squares maximum likelihood estimation
- Kalman filter is the preferred estimation technique for real-time estimation or parameter updates
 - Mix new information with prior information
 - Update previously calibrated parameters using a zero velocity update
 - Update parameters and navigation states using external aids
- The states and their covariances are propagated using the state dynamic equations

Inertial Navigation Computations

- **Accelerometer outputs are transformed from the ISA frame to a navigation frame**
 - Using the gyroscope outputs to keep the ISA inertially oriented or local level, or to propagate the attitude quaternion in the case of a strapdown system
 - Corrected for centripetal and angular acceleration
 - Typical navigation frames are inertial, earth fixed, or local level
- **High computation rate required for a strapdown INS**
 - To prevent compensation errors for sculling and coning due to linear and angular vibration
- **In the navigation frame the modeled gravitational acceleration is added to the accelerometer outputs**
- **The result is numerically integrated to obtain the vehicle motion**

External Aids

- Inertial navigation errors grow with time, but can be bounded by external aids
- External aids include:
 - Altimeters, depth meters, odometers
 - Air speed indicator, radar, sonar, speedometer, speed log
 - Map matching, terrain recognition
 - Magnetometer, magnetic compass
 - Star sightings
 - Space- or terrestrial-based radio navigation systems
- Zero velocity update
- Free fall

Inertial Guidance

- **Guidance**
 - Generation of command signals for controlling vehicle motion and attitude to follow a trajectory
- **Lambert guidance**
 - Commands a ballistic missile to follow the conic section trajectory in the $1/r^2$ gravitational field of the earth that goes between the launch and target points in a specified time
- **Terminal guidance**
 - Uses sensors that give target information relative to the vehicle
- **Autopilot**
 - Autonomous control of a vehicle's attitude and/or velocity
- **Flight control**
 - Carrying out of guidance and autopilot commands

Published Standards

- **Inertial sensor terminology**
- **Spinning wheel gyros**
 - Single degree-of-freedom, spring restraint
 - Single degree-of-freedom, rate integrating
 - Dynamically tuned gyros (DTG)
- **Sagnac effect gyros**
 - Ring laser gyros (RLG)
 - Fiber optic gyros (FOG)
- **Coriolis vibratory gyros (CVG)**
- **Angular accelerometers**
- **Linear accelerometers**
- **Precision centrifuge testing**

Other Proposed Standards – P1554

- **Recommended practice for carrying out gyroscope and accelerometer tests**
- **Inertial sensor test equipment**
 - Test tables and fixtures, centrifuges and vibrators, environmental chambers, radiation test facilities
- **General and sensor specific electronics**
 - Continuous counters, phase-locked loops, voltage-to-frequency converters, voltmeters and A/D converters, etc.
- **Data acquisition computers and software**
 - Including real-time digital filtering and automatic test equipment
- **Data analysis techniques**
 - Graphical, least squares, power spectral density (PSD), Allan variance

IEEE Gyro Standards Maintained by the GAP (1 of 2)

- 292-1969† IEEE Specification Format for Single-Degree-of-Freedom Spring-Restrained Rate Gyros**
- 293-1969† IEEE Test Procedure for Single-Degree-of-Freedom Spring-Restrained Gyros**
- 517-1974† IEEE Standard Specification Format Guide and Test Procedure for Single-Degree-of-Freedom Rate-Integrating Gyro**
- 529-1980† IEEE Supplement for Strapdown Applications to IEEE Standard Specification Format Guide and Test Procedure for Single-Degree-of-Freedom Rate-Integrating Gyros**

† Re-affirmed in 2000

IEEE Gyro Standards Maintained by the GAP (2 of 2)

- 647-1995** **IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Laser Gyros**
- 813-1988†** **IEEE Specification Format Guide and Test Procedure for Two-Degree-of-Freedom Dynamically Tuned Gyros**
- 952-1997‡** **IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Interferometric Fiber Optic Gyros**
- 1431-2004** **IEEE Standard Specification Format Guide and Test Procedure for Coriolis Vibratory Gyros**

† Re-affirmed in 2000

‡ Re-affirmed in 2003

Other IEEE Standards Maintained by the GAP

- 528-2001** IEEE Standard for Inertial Sensor Terminology
- 671-1985‡** IEEE Standard Specification Format Guide and Test Procedure for Nongyroscopic Inertial Angular Sensors: Jerk, Acceleration, Velocity, and Displacement
- 836-2001** IEEE Recommended Practice for Precision Centrifuge Testing of Linear Accelerometers
- 1293-1998‡** IEEE Standard Specification Format Guide and Test Procedure for Linear, Single-Axis, Nongyroscopic Accelerometers

‡ Re-affirmed in 2003

Proposed IEEE Standards Under Development

By Project Authorization Request Number

- P1544** **Recommended Practice for Inertial Sensor Test Equipment, Instrumentation, Data Acquisition, and Analysis**
- P1559** **Standard for Inertial System Terminology**