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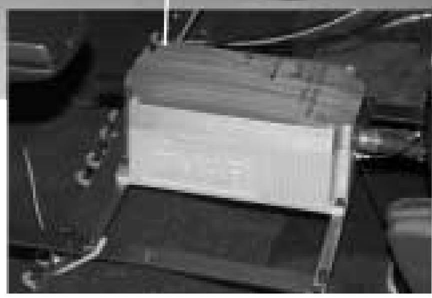
Inertiale Messsysteme mit faseroptischen Kreiseln für Fahrdynamik und Topologiedaten-Erfassung

Inertial Measuring Systems with Fibre-optic Cyroscopes

It is hard to imagine modern motor vehicle development without the use of gyroscope platforms as a means of vehicle motion analysis. The properties of today's inertial measuring systems that are used for motion analysis, stabilization and 3D topology surveys are the subject of this article. As an example, we will describe the motion analysis of motor vehicles (the so-called "elk test") that use the latest version of iMAR gyroscope platforms manufactured by iMAR GmbH, St. Ingbert (Germany). Precise sensor technologies for measuring even highly dynamic driving manoeuvres in combination with sophisticated mathematical procedures support the measuring engineer in the execution of even the most demanding measuring programs.

By Edgar von Hinüber

1 From Gyroscopes for Ships to Miniature Strap-Down Systems

For many years, inertial measuring systems have been used for navigation tasks in the air, at sea or on the ground. These systems measure the acceleration along the trajectory of a motor vehicle with the aid of sensor technology. The speed and position of a body can be determined by integration of its acceleration over time within an earth-fixed navigation coordinate system.

The first inertial measuring systems were so-called north-seeking gyros. In 1913, the first passenger ship was equipped with an Anschütz gyro compass (named after its inventor), which comprised two heavy twin balls rotating in opposite directions. Forty years later, in 1953, the first successful flight using an inertial navigation system in platform technology took place from Massachusetts to California. Almost forty years later, in 1992, the iDIS-FV from iMAR (based in St. Ingbert/Saarbrücken, Germany) was presented to the professional world as the first inertial measuring system in strap-down technology for vehicle motion analysis with fibre-optic gyroscope technology and a VMEbus process computer. Four years later came the iDIS-FC, the new version with an integrated micro-controller, **Figure 1**.

Today, in 2002, the third generation of inertial measuring systems for vehicle motion analysis is being introduced to the market. It features half the weight of previous versions, a three-times higher accuracy, higher sampling rates with less signal delay and substantially enhanced functionality.

2 What is Inertial Measuring Technology?

According to Newton's second axiom, the motion path of a body can be precisely determined if at all times all forces acting upon this body are known and if the starting position and initial speed are taken into consideration at the start of the observations. But in principle it is not possible to differentiate between inert and gravitational mass in a motion system. Basically, inertial measuring technology determines the forces acting on a body in motion according to Newton's second axiom using accelerometers to derive the motion from these data . When navigating in a gravitational field, the value and direction of the gravity vector (gravity $g \approx 9.81$ m/s^2 in an earth-fixed measurement) in reference to the body in motion has to be known at all times. In a rotating reference system, the rotation rate vector also has to be known (earth rotation rate: $\omega_E = 15.041$ °/h).

In terrestrial navigation, the acceleration of gravity is constantly co-measured by accelerometers as disturbance and has to be compensated for. This is achieved by constantly registering the alignment of the body in reference to earth's gravity field using fixed (or "strap-down") gyroscopes. Consequently, an inertial measurement system in its simplest configuration consists of three orthogonally arranged accelerometers to determine the acceleration vector and of three orthogonally arranged gyroscopes to determine the rotation rate vector of the body, if motions in all six degrees of freedom of the body are permitted. As the orientation of the measuring system is to be referenced to an earth-fixed coordinate system – usually the local horizontal reference system – the earth's rotation rate vector also has to be compensated for in the rotation rate vector, measured by the gyroscopes. The compensations are calculated using two simultaneous vector-valued differential equations.

Figure 2 is a block diagram of the iDIS-FMS series' inertial measuring system. One can see its modular architecture, which allows the integration of customized features.

Major design features of the iDIS-FMS are its high sampling rate of 400 Hz, the large measuring range of ± 500 °/s and ± 10 g, the internal or external GPS, an integrated odometer interface, the CAN bus and Ethernet interface as well as an open interface application software based on Windows. iDIS-FMS has been developed for various applications. Devices of this series are used for vehicle motion analysis ("elk test") as well as the stabilization of antennas on ships, the guidance of aircraft and underwater vessels (drones and RPVs) and the determination of position and control of service robots (e.g. in pipelines).

Figure 3 shows this lightweight, handy and at the same time robust measuring system. It complies with all environmental rules for such devices per the IP 67 system of protection and is operated with a voltage of between 10 and 34 V and a power consumption of only 30 W.

In accordance with the requirements of measuring field engineers, the following data are among the output resulting form internal real-time calculations (all with time stamp):

- Useful rotation rate in vehicle-centred coordinate system (earth rotation rate compensation applied)
- Useful acceleration in vehicle-centred coordinate system (gravity compensation applied)
- Angular orientation in space (roll, pitch, yaw) of the vehicle in reference to its local, earth-fixed coordinate system (so-called Eulerian angles)
- Odometer-longitudinal velocity in vehicle's coordination system
- Position in local and world coordinate system (x/y/z and longitude/latitude/height)
- Output of measuring values centred on the vehicle's gravitational centre or on any other point of the vehicle

3 Coordinate Systems

In strap-down technology, we differentiate between several coordinate systems. The four most important are:

1. Earth-fixed, global world coordinate system
2. Earth-fixed, local horizontal coordinate system
3. Sensor coordinate system
4. Vehicle coordinate system (also called body coordinate system)

In order to determine the global position of a vehicle, the WGS84 coordinate system supported by GPS (satellite-aided Global Positioning System) should be used, in which each position is precisely defined by longitude, latitude and height (world coordinate system).

In order to determine metric distances, an earth-fixed local horizontal coordinate system in which the surface formed by the x- and y-axis of this coordinate system is tangential to earth's surface on the testing site should be used. The longitude and latitude of the testing site define the origin of this earth-fixed coordinate system. For navigation algorithms, only the latitude is relevant, as the north-south axis through the earth's poles forms a symmetrical axis for the quasi-stationary navigation problem. By definition, the x-axis of the coordinate system is directed towards east, the y-axis towards north and its z-axis up (ENU).

The sensor coordinate system, **Figure 4**, is defined by the position of the gyroscopes and accelerometers within the measuring system. All measured values refer to the sensor coordinate system and have to be transformed into a different coordinate system which can be more easily interpreted. Besides the world or horizontal coordinate system, the vehicle coordinate system used in the automotive industry and defined in DIN 70 000 is such a system. The direction of its x-axis is the forward direction of the car, its y-axis goes to the left (in reference to the forward direction) and its z-axis is positioned orthogonally on top of the two other axes in the upward direction.

The transformation from the sensor or vehicle coordinate system into the earth-fixed coordinate system is carried out internally in the system with so-called quaternia or direction cosine matrices. The angular presentation is very efficient from the mathematical point of view; for the user it is of very little help, however. Therefore, Eulerian angles are usually used for presenting the position of a vehicle in space. These roll, pitch and yaw (RPY) angles are defined as follows.

RPY angles according to DIN 70.000 (body frame):

Yaw angle ψ: "Psi" angle around the z-axis of the world coordinate system (upward direction). This is the first rotation required for the transformation from the world system into the sensor system.

Pitch angle ϕ: "Theta" angle around the y-axis of the world coordinate system rotated by ψ (≈ angle around the y-axis of the sensor coordinate system for small lateral angles).

Roll angle ϕ: "Phi" angle around the x-axis of the sensor coordinate system (third rotation).

It is important to understand that the

vehicle orientation in the world coordinate system is described by the RPY angles after three successive rotations with the standard world coordinate system (ENU: x east, y north, z up) as the starting point. After three successive rotations of the single axis, the spatial position of the vehicle is achieved. In this context, the fixed sequence of these rotations is essential. The measuring system of course also determines the angles in the case of simultaneous rotations around all axes by solving a simultaneous differential vector equation.

4 Motion Analysis Sensors

Only servo accelerometers are used as acceleration sensors for precise motion analysis. Their internal closed-loop structure renders excellent linearity in a measuring range which covers more than 5 decades (± 20 g measuring range with a resolution of 10 µg) in these applications. They are shock-resistant (100 g) and have proven their high reliability in military and civil applications over many years.

Two types of sensors, based on two different effects, can be used as gyroscopes. Their advantages and disadvantages are explained briefly in the following.

- The vibro gyroscope (the term "gyroscope" should not be confused with "spinning gyro bodies") is based on the Coriolis theorem of mechanics: An accelerometer which is moved in an orthogonal direction of its sensitive axis at a speed v is accelerated if it is given a rotation rate around the third orthogonal spatial axis which is sensitive to speed and acceleration, **Figure 5**. Usually, the speed is generated in the form of a harmonic oscillation with a piezo vibrating actuator or with capacitive acceleration. Today, the vibro gyroscope is frequently used in low-cost devices. In contrast to fibre-optic gyroscopes in these applications, noise, a large temperature-dependent drift (up to 3 °/s over temperature) and an obvious temperature-dependent scale factor with a small bandwidth are uncritical. Influences of translator acceleration, vibration or structure-borne noise can have a negative impact on these gyroscopes, as their measuring system is based on vibration and acceleration measurement.
- Optical gyroscopes are based on the Sagnac effect. This effect can be explained using the functional schema of an optic-optic gyroscope: **Figure 6** shows the basics of such a device. It comprises a light-emitting super luminescent diode (SLD), beam splitters, a modulator, the fibre coil which covers the effective surface A, and an interference detector. Through the positioning of the beam splitters, the light emitted by the SLD with the wavelength λ is split in two beams, both travelling along the coil in opposite directions. If the whole arrangement is rotated around the normal vector of the coil with the angular velocity w, the path of one beam becomes shorter while the path of the other beam becomes longer. The resulting differences in lapse of time cause a phase shift between the two light waves. The interference detector recognizes this and measures the angular velocity. With feedback control of the measured phase shift to an optical phase-shift element (so that the sensor works internally on a constant phase), a so-called closed-loop optic-optic gyroscope is the result.

Compared to mechanical or piezoelectric devices, optical gyroscopes have the advantage that the sensing element is not subject to any mechanical strain. It is largely insusceptible to vibration and acceleration. This explains why optic-optic gyroscopes are used for precision measuring systems.

Single-axial optic-optic gyroscopes are frequently used by the automotive industry to determine the yaw rate. A description would lead too far for this article. Further information may be found under www.imar-navigation.de .

5 Measuring Deviation and Measuring Results

When using inertial measuring technologies, one should be familiar with the basic measuring deviations of these systems.

The gyro drift is the error angle per time unit of a gyroscope. If a gyroscope is at rest with an output offset of 3 °/h (rotation rate offset), then the gyro drift is 3° per hour or 1° in 20 minutes (without aiding).

The random walk is a measuring deviation of the gyro, which is the consequence of integrating white random noise. The noise of the rotation rate can be calculated as 1-sigma-value in reference to an output bandwidth f[Hz]

r[°/s] = RW[°/sqrt(h)] x sqrt(f[Hz]) x 60/3600.

Looking closer at the drift of a pitch or roll gyroscope (usually y-axis or x-axis), one will notice that this drift causes the actual angles to be overlapped by an error angle which increases with the measuring time and drift. The precision of the attitude measurement in space (i.e. pitch and roll angle) is decisive for the precision of the gravity compensation in the measured acceleration signals. Therefore, the measuring deviation of the acceleration after gravity compensation increases with the duration of the measurement. An angle error of 0.06 ° results in an acceleration error on the horizontal channels of approximately 1 mg.

However, even a very slight gyro drift is in most cases not small enough to carry out longer measuring cycles and achieve the required measuring accuracy. Therefore, iMAR's so-called adaptive aiding is used to eliminate the drift from the measuring results. In the case of land vehicles, external speed data are recorded optionally to correct the position angle. Using these data, the longitudinal and lateral acceleration can be estimated, which, together with the inertial measuring system, allow the correction of the position angle. If available, GPS is used for the drift compensation of the heading gyro. Due to its high sensor accuracy, the iDIS-FMS does not, however, require continuous GPS availability, as other systems do.

Figure 7 shows the measurement of a typical “elk test”. These data are recorded with the iMAR platform iDIS-FMS, which is used by ZF Lemförder Fahrwerktechnik (a supplier of chassis components, modules and complete axle systems). In combination with the measured steering angle, they allow the user to assess, among other things, the lateral dynamic transmission behaviour and the roll steer effect of a car. Additionally, all movements of the car body are recorded for use as evaluation criteria for vehicle dynamics and comfort.

6 iDRPOS: 3D Topology Surveying

The iDRPOS algorithm, which can be optionally integrated into the iDIS-FMS, uses a special Kalman filter for advanced aiding in addition to the general odometer aiding. Therefore, it can determine both driving dynamics data and topological path data. The measuring system also renders reliable position data even if the GPS is temporarily unavailable. There is no impact on the accuracy of measuring vehicle-dynamic related data such as rotation rates, accelerations or attitude, should the GPS be temporarily unavailable – quite in contrast to low-cost systems with micro-mechanical gyroscopes or low-cost optic-optic gyroscopes whose accuracy primarily depends on GPS (satellite detection).

Due to the high accuracy of optic-optic gyroscopes and accelerometers, iDIS-FMS, suitable for the analysis of vehicle dynamics, use GPS only as an additional data source. They are also largely insusceptible to GPS interruptions (for example multipath). **Figure 8** shows the online estimated standard deviation of measuring data (odometer scale factor, position, heading).

For further information, refer to www.imar-navigation.de.

The quality of an inertial measuring system, however, also depends on its user interface. Therefore, when designing the new generation of these measuring devices, apart from the hardware a universal and modular interface was also developed which is used consistently in all iMAR measuring systems starting with version 2002. It enables the user to modify parameters such as sampling rates, aiding criteria, threshold values, etc., to submit commands (e.g. Start/Stop of the alignment) and to output time-related or distance-related measuring data (e.g. attitude, acceleration, rotation rate, odometer speed, etc.).

For standard applications, the software NAV_Command (for Windows‰) is provided, which is easy to use for both the occasional and experienced user, **Figure 9**. The open interface allows the user to integrate the measuring systems (with an optional DLL) directly into his or her own application. We would like to point out, however, that the inertial algorithms run on the hardware (process computer) of the measuring system with a real-time operating system. Windows on an external laptop or PC serves only for user prompts and display purposes as well as for saving data.

7 Summary

The advanced design of the optic-optic gyroscopes as well as their commercial availability as a high-volume mass product from the manufacturer in Germany / St. Ingbert opens up a huge field of innovative applications for this gyroscope technology. It was demonstrated that these optic-optic gyroscopes with scale factor errors of <300 ppm and drifts of between 1 and 3 °/h may be used for the traditional tasks of stabilization and navigation as well as dynamic and static motion analysis of vehicles of any kind and for topology surveying. The execution of measurements and interpretation of measured results becomes considerably easier due to the use of strap-down algorithms and procedures for signal processing as well as the introduction of custom coordinate systems and easy-to-use software.

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