Inertial Technology: Sensors, Algorithms, and Integration

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ABSTRACT

Inertial Measurement Units (IMU) are the core component for all inertial technology. Usually consisting of three perpendicular accelerometers and three perpendicular gyroscopes in a strapdown configuration, IMUs are available on the market in a wide range of qualities for various applications.

Based on IMUs, different algorithms are used to combine the inertial measurements with other sources of information, e.g. air-data computers (ADC), magnetometers, global navigation satellite systems (GNSS) or radar altimeters. This allows the implementation of various inertial systems, which are in widespread use in a variety of different applications. In aviation, the most prominent systems using inertial technology include Inertial Navigation Systems (INS) and Attitude & Heading Reference Systems (AHRS).

Inertial Navigation Systems (also called Inertial Reference Systems – IRS) are independent sources to determine the current position. For this, the acceleration measurements are integrated twice to obtain a position solution based on a given initial state. Thus, Inertial Navigation Systems require a significant alignment time prior to the flight and are prone to small measurement errors (which are amplified by the dual integration significantly). Nowadays, most Inertial Navigation Systems use GNSS inputs whenever possible for increased accuracy. For operations without GNSS, the achievable positioning performance directly relates to the quality of the IMU used. For an unaided Inertial Navigation System intended to provide guidance for a longer period of time, sophisticated high-quality IMUs are required.

If not the position but the attitude of the aircraft is the primary concern, an IMU can be operated as an Attitude & Heading Reference System. This usually includes the use of magnetometers and other input sources. As no positioning has to be performed, lower grade measurement units can be used compared to Inertial Navigation Systems. This works well in most situations, but has some disadvantages to be mitigated operationally.

When implementing a measurement aircraft for flight inspection, the choice of an inertial integration algorithm has to be driven by the requirements. If robust positioning even in absence of GNSS is required, a different type of sensor will be required than for scenarios where attitude readouts are required only.

This paper will explain the different types of inertial measurement units and integration techniques, and will detail the pros and cons of each, especially for the use in flight inspection systems.

INTRODUCTION

Inertial technology is based on the inertia of bodies, i.e. it requires forces to change the linear or rotational movement of a body. This is the basic principle of gyroscopes, where a rotating mass remains static in an inertial reference frame as long as no forces are applied. Basic gyroscopic instruments like attitude indicators, gyrocompasses or turn indicators have been installed in virtually all aircraft since the 1940s.

Since then, inertial technology has found widespread use in the form of inertial navigation systems (INS) or inertial reference systems (IRS). Historically, these devices used a spinning object in a gimballed frame. Such a gimbal platform remains its orientation in space regardless of the aircraft's orientation. By mounting three perpendicular accelerometers on this platform, early (gimballed) inertial navigation systems measured the accelerations in an inertial frame directly. By integrating these acceleration measurements twice, and given an initial position/velocity state, the current position can be calculated directly without requiring any external infrastructure. The mechanical efforts required to minimize errors as far as possible are tremendous, making gimbaled platforms expensive, power consuming and huge.

The next step in the development of inertial navigation system was to remove moving parts, including the gimbals. Such strapdown systems use three perpendicular angular rate sensors to measure rotational rates as well as three perpendicular accelerometers to measure linear accelerations. All sensors are fixed in the aircraft and provide their measurements in an aircraft-fixed coordinate system. In order to convert the acceleration measurements into an inertial frame (i.e. like in a gimbal platform), the angular rate measurements are integrated first to obtain a current attitude (the so-called attitude update).

Of course, integrating measurements twice also integrates any errors twice, making pure inertial navigation systems drifting away. Thus, the amount of drift (or the period in which a certain positioning accuracy can be achieved) is a straightforward way to classify the performance of an INS.

INERTIAL MEASUREMENT PRINCIPLES

Modern "strapdown" inertial navigation is based on measurements of a body's acceleration and angular rate. The sensors to measure this are called accelerometers and gyroscopes. Both sensors are available in a wide variety of types, performances and costs.

Accelerometer

An accelerometer is a sensor to measure the current acceleration in one axis. This is usually accomplished by measuring the force of a known sample mass.

Accelerometers are available in different forms, measurement principles and performance grades. They range from cheap and small consumer-grade micro electric-mechanical systems (MEMS) up to expensive high-quality sensors.

The overall performance of accelerometers can be classified using its bias, given in multiples of gravity (g). Typical values often used for classification are shown in Table 1.

Table 1: Typical Accelerometer Grades (values taken from [2])

Grade	Marine	Navigation	Intermediate	Tactical	Consumer
Accelerometer Bias	≤ 0.01 mg	0.03 – 0.01 mg	0.1 - 1 mg	1 - 10 mg	> 3 mg

Gyroscope

Rate gyroscopes measure the angular rate of turn around a specific sensitivity axis.

Comparable with the accelerometers described before, gyroscopes using different principles and performances are available on the market too. The performance of a gyroscope is often graded by its bias; typical classification values are shown in Table 2.

Table 2: Typical Gyroscope Grades (values taken from [2])

Grade	Marine	Navigation	Intermediate	Tactical	Consumer
Gyroscope Bias	0.001 °/h	0.01 °/h	0.1 °/h	1 - 100 °/h	> 100 °/h

Inertial Measurement Unit

An Inertial Measurement Unit (IMU) is a combination of (usually) three accelerometers and three gyroscopes. These are mounted so that the sensitivity axes of the gyroscopes and accelerometers are mutually orthogonal to each other in order to measure in all six degrees of freedom. IMUs are manufactured with very strict requirements on the axes orientation as even small mounting errors have a significant influence on the overall performance. In addition, the overall performance of an IMU is dictated by the quality of the individual sensors. Following the same performance grades as shown for the individual sensors, the achievable performance for free-inertial positioning (horizontal only) is shown in Table 3. Please note that intermediate, tactical and consumer graded IMUs are not intended to be operated this way.

Table 3: Typical Free-Inertial Long Term Stability for Different IMU Grades

Grade	Marine	Navigation	Intermediate	Tactical	Consumer
Position Error	1 NM/day	1 NM/hour	-	-	-

It has to be noted that the typical classification grades shown in Table 1 and Table 2 are not ultimately sufficient to compare the detailed behavior of different inertial sensors, as their overall performance depends on various characteristic properties (which are often not publically available or determined comparably).

INERTIAL SYSTEMS

Inertial technology is used in various aircraft instruments, beginning with classical instruments like attitude indicators or gyrocompasses. However, most modern aircraft use strapdown inertial measurement units in combination with other sensors. The measurements of the IMU and of the external sensors are combined (hybridized) in a Bayesian filter, which estimates the desired states (the so-called state vector) along with their error bounds (the so-called covariance matrix). Figure 1 shows the general integration principle for combining IMU measurements with other sensors. Most implementations use non-linear Kalman filters like an Extended Kalman Filter (EKF) or an Unscented Kalman Filter (UKF) for this.

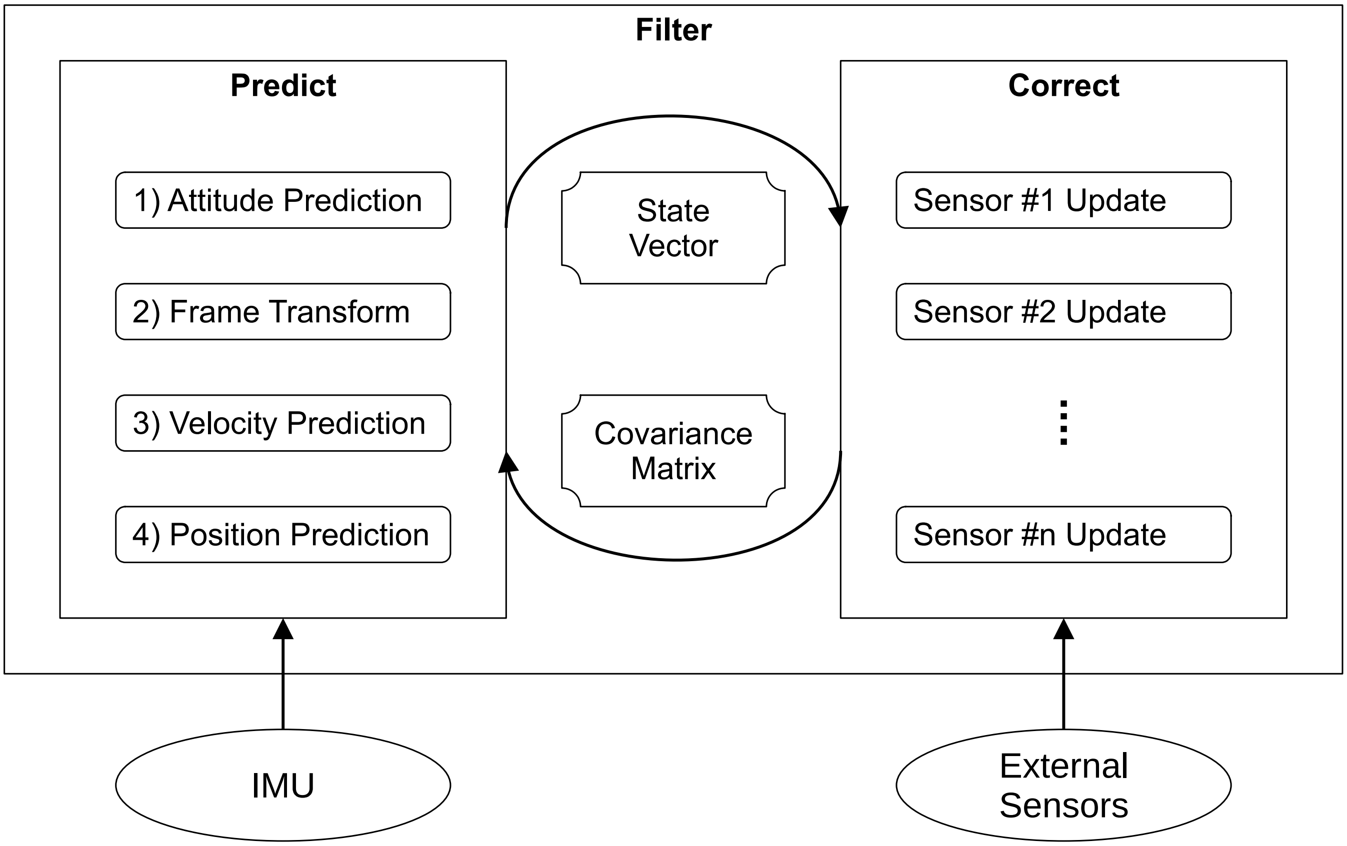

Figure 1. Generalized Integration Principle of Inertial Navigation with Other Sensors

Kalman filters generally use a two-step approach. The first step is the prediction step, where the high-frequency periodic measurements of the IMU are used to predict the attitude, velocity and/or position for the current time. If available, measurements of external sensors are incorporated next in the update step. Both steps are independent from each other.

The state vector contains all information in which the user is interested in, plus any states that are estimated on the way to improve the overall performance. As a minimum, the state vector usually incorporates the current position, velocity and attitude in a specific navigation frame, but additional state vector items can be included if necessary.

The prediction step can incorporate up to four distinct steps. Firstly, the attitude prediction step uses the measurements of the gyroscopes to update the attitude estimation, so basically the pitch, roll, and yaw angles. Secondly, the newly estimated attitude is used to transform the measurements of the body-fixed accelerometers into the desired navigation frame. Thirdly, the accelerometer measurements are used to update the velocity estimation. Lastly, the velocity is integrated over the sampling time in order to obtain a new position prediction. It is the position update step which is most affected by any IMU errors, so that the position accuracy degrades fastest compares to the other elements of the state vector. Not all prediction states have to be done for all implementations. A prediction always results in an increased uncertainty of the estimated states.

The update step uses the measurements of external sensors to correct the state estimation. In principle, various external sensors can be used to correct one or multiple states. External updates usually reduce the estimated uncertainty. The actual sensor(s) to be integrated can be chosen according to the application and its requirements.

Based on this generalized integration principle, different actual implementations are possible. In order to distinguish between the implementations, the state vector, the prediction steps, the used external sensors as well as their update algorithms must be taken into consideration.

Attitude Heading Reference System (AHRS)

An AHRS is a system for providing the attitude and the heading to electronic flight instruments (EFIS), replacing legacy indicators like the gyrocompass, turn indicator, and attitude indicator.

Simple AHRS implementations do not provide position and velocity outputs, but only estimate the attitude. This way, as no velocity or position update is required, low-grade IMUs can be used to provide sufficient attitude accuracy. Typical AHRS devices for aircraft integration incorporate magnetic field sensors that are used to correct the heading estimate. AHRS sensors are thus rather inexpensive and are predominantly found in smaller aircraft. Thus, the positioning of such equipped aircraft has to rely on other systems (like VOR/DME or GNSS).

Magnetometers can be affected by various error sources so that their integration into an aircraft can be challenging. This is why primary AHRS installations in aircraft use internal algorithms specifically adapted to regular maneuvers and operation. Thus, special circumstances or maneuvers (e.g. during a flight inspection) can lead to incorrect attitude estimates. Some AHRS implementations even allow pilots to deactivate magnetic updates of the AHRS, making the AHRS running freely as a directional gyro. This can however affect the overall performance significantly.

Inertial Navigation Systems (INS)

Inertial navigation systems for aircraft installation are also often referred to as “Inertial Reference Systems” (IRS). These expensive systems provide continuous position, velocity and attitude outputs even without any ground-based infrastructure. Only the barometric altitude, which is usually fed to the INS from an aircraft’s Air Data Computer (ADC), is used as external input. The barometric altitude is crucial because the vertical positioning is unstable and degrades fast without external aiding.

The main purpose of an INS is to enable an aircraft to fly intercontinental routes without the need for ground infrastructure, e.g. for polar or transatlantic / transpacific routes. This implies that these systems use at least navigation grade IMUs in order to achieve a positioning drift of less than one NM per hour – without any external positioning update. Meeting the stringent required navigation performance (RNP) requirements results in expensive and (possibly) export-restricted equipment.

Providing the highest performance, aircraft inertial navigation systems are the pinnacle of airborne inertial technology. Their cost and installation constraints (volume, weight, power) however result that INS are mainly installed in long-range aircraft only.

Hybrid Systems

So-called hybrid systems combine an IMU with additional complimentary sensors. Most dominantly, this is the combination of an IMU with global navigation satellite systems (GNSS) like the GPS. However, other additional sensors (e.g. air data computers, magnetometers, radar systems, optical systems, odometers etc.) can be integrated as well.

By combining systems with complimentary characteristics, the hybridization can benefit from the respective advantages of each system. When for example combining an IMU with a GNSS receiver, hybrid systems feature the high update rate of the inertial system as well as the absolute positioning accuracy of the GNSS.

Next to the position, velocity and attitude, the state vector of (IMU-GNSS) hybrid systems usually includes the GNSS timing error(s) and additional scale factors for refining the inertial measurement unit. Depending on the external sensors, other parameters can be estimated as well. This way, hybrid systems allow for very flexible operation.

This makes hybrid systems an attractive system for meeting specific requirements with lower-grade inertial equipment. Thus, the grade of the IMU dictates the overall performance without external updates. A hybrid system is typically selected based on the performance requirements in case of missing GNSS updates, i.e. for which duration the hybrid system can ensure a certain RNP level without GNSS.

Modern hybrid systems (especially those not specifically designed as primary aircraft equipment) can be configured flexibly using different interfaces. This includes (but is usually not limited to) the ability to enable or disable specific external sensor updates and prediction update steps. This is why those hybrid systems usually can be configured to incorporate only barometric updates of an air data computer while performing all prediction steps, making it effectively a pure inertial navigation system (even though the overall performance has to be looked at specifically in this case). On the other side, it is also often possible to integrate magnetometer updates and to disable all but the attitude update, effectively resulting in an AHRS implementation.

ALIGNMENT

The alignment of any inertial technology describes the process of determining the initial orientation of the user. An alignment has to be performed prior to each use in order to determine a valid initial attitude. Both static and dynamic alignments are possible, depending on the application.

Static alignment requires the user to stand still for the complete alignment duration. In this case, gravity is the only force affecting the accelerometers so that the roll and pitch angles can be determined. The heading can be initialized using magnetometers or using a technique called gyro-compassing. Here, high-grade gyroscopes are used to measure the rate of rotation of the Earth (approx. 15° per hour) in order to determine the current true heading. In addition, the current position must be entered as initial state in this case (unless coupled with GNSS or other absolute positioning sensors).

Dynamic alignment is only possible for systems with absolute positioning input (e.g. with GNSS as external sensor). In this case an alignment can be performed while in (stationary) flight. Most implementations require the user to fly straight and level for this.

Both kinds of alignment require a certain period of time that depends on a variety of factors (integration technique, external positioning input, IMU grade, required attitude accuracy, geographic latitude). The required amount of time usually varies between below one minute (e.g. for GNSS-based AHRS implementations) and up to 15 minutes (for free-inertial systems requiring a very precise gyro-compassing).

Especially in the case of static alignment for positioning systems, it is crucial to remain static for the whole alignment duration, and not even changing e.g. the loading state of the aircraft. This is why such installations usually include two provisions for best operational handling. On the one hand, a flight deck indication is usually available so that the pilots are aware that they may start moving the aircraft only after alignment has finished. On the other hand, the inertial system often includes batteries for short-term power supply. This for example allows performing the alignment prior to engine start and maintaining its aligned state even in case of brief power outages or bus switchovers.

FLIGHT INSPECTION IMPLICATIONS

Various inertial-based equipment is used in flight inspection aircraft. This ranges from simple AHRS equipment used also for the electronic flight instruments up to navigation-grade INS installed only for flight inspection applications.

Primary AHRS installations are often already installed as primary equipment in the base aircraft and can be interfaced to get attitude information. For positioning, an extra GNSS receiver is then used. This is a rather inexpensive solution with an overall performance sufficient for many operations.

When using an AHRS system, positioning can only be performed using GNSS. In case of GNSS outages (e.g. due to external radio frequency interference), an AHRS-based installation cannot provide a continuous positioning and might invalidate certain portions of an inspection flight.

In addition, as primary AHRS installations are designed for regular air navigation, their usability can suffer from low update rates, delayed outputs and drifts during typical flight inspection maneuvers (refer to [3] for details). As even small attitude errors can lead to significant errors during flight inspection, and as each AHRS model has different characteristics, the overall AHRS performance needs to be assessed carefully in order to ensure a sufficient level of performance during flight inspections. This also includes the integration into an AFIS software and the combination with other sensors.

In contrast, some flight inspection aircraft have an extra navigation-grade INS installed only for flight inspection operations. With a position drift of less than one NM per hour, these are extremely reliable and allow for continuous operation completely without GNSS. However, without GNSS backing, the performance degrades continuously after the alignment so that the requirements on a specific positioning accuracy cannot be met after certain time. Depending on the required performance for the flight inspection, this can mean that the usable time after alignment could be limited severely.

This is why hybrid GNSS+inertial systems are considered to be the best match for flight inspection use. Hybrid systems can use GNSS for absolute accuracy (even in combination with real-time kinematics or SBAS corrections), can integrate additional sensor information (like magnetometer measurements, data from an air-data computer, or information derived from optical systems), and can even provide continuous service in case of GNSS outages. In principle, different IMU grades can be used for these systems, but the IMU quality directly affects the system’s capability to meet performance requirements in GNSS-denied situations. The longer a certain level of performance has to be met in case of GNSS outages, the higher-graded IMUs need to be selected. With a wide variety of hybrid positioning product commercially available, providers of flight inspection systems can choose a system matching the customer requirements best.

Another non-technical constraint for selecting a customer’s inertial system can be export control. Especially maritime and navigation grade IMUs are often not only covered by dual-use export regulations, but might also be covered by restrictions due to the International Traffic in Arms Regulations (ITAR). Export constraints thus have to be taken into account very carefully.

CONCLUSIONS

This paper gave a brief introduction into inertial technology and its use in modern aircraft. Based on different grades of inertial measurement units and different integration schemes, different products can be installed in flight inspection aircraft.

Primary AHRS systems are the most cost-efficient solution (if already being installed in a flight inspection aircraft). However, such installations suffer from some shortcoming that have to be addressed carefully for reliable flight inspection performance.

Hybrid inertial systems on the other hand provide good overall performance and are available in different quality grades. This allows selecting hybrid inertial systems for flight inspection aircraft based on the requirements for overall performance without GNSS aiding.

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