If you want to use an inertial measurement system...

... which technical data you should analyse and compare before making your decision

by Dr.-Ing. Edgar v. Hinüber, CEO iMAR Navigation GmbH

Keywords: inertial navigation system, inertial measurement system, inertial measurement unit, attitude heading reference system, inertial sensor, gyroscope, accelerometer, angular random walk, bias, drift, free inertial, unaided inertial navigation, aided navigation, INS, IMU, IMS, AHRS

In fact, for unskilled users as well as for advanced users of inertial technology, it is often very difficult to get the right "feeling" which one of all the different provided inertial measurement systems or inertial navigation systems or attitude heading reference systems or inertial measurement units or at least inertial sensors will meet their application requirements best and most economically.

With this article we try to help you to understand the physics behind those inertial navigation or inertial measurement systems and sensors and also to validate the datasheets of the vendors by yourself, to make your best technical and economical selection.

Introduction into Inertial Measurement Technology:

Inertial navigation and guidance systems were originally developed to control rockets, today they are used in many applications from horizontal directional drilling up to space vehicle navigation. Today everybody is in touch daily with inertial technology, for example every modern car contains at least one gyro and two accelerometers for ESP (electronic stability program or more complex advanced driver assistance systems [ADAS]) or for the airbag control to make travelling as safe as possible even in difficult environment. Also every smartphone contains accelerometers and gyroscopes today.

A typical inertial navigation system uses a combination gyroscopes, to compensate the x, y and z accelerometer data regarding gravity, i.e. to solve a large set of differential equations to convert these readings into estimates of velocities, position, attitude and heading, starting off from a known initial position of latitude and longitude.

Today’s implementation of inertial navigation systems (INS) is typically in so-called strap-down technology, where all inertial sensors (gyros and accelerometers) are stiff mounted (strapped down) on the vehicle. In the past the systems had been designed in so-called gimballed technology, where the gyros had been used to stabilize the accelerometers mechanically in space. In strap-down systems the stabilization is done mathematically, and therefore all inertial sensors suffer the full vehicle’s dynamics. Due to missing mechanical gimbals the strap-down systems are much more robust in operation than the gimballed systems, but the requirements to sensor range and sensor scale factor as well as sensor robustness are higher.

All inertial navigation systems suffer from the integration of drift over time, because small errors in measurements are accumulated into progressively larger errors in velocity and especially position due to double integration over time.

Inertial navigation may also be used to supplement other navigation systems, providing a higher degree of accuracy than is possible with the use of any single navigation system. For example, if, in terrestrial use, the inertially tracked velocity is intermittently updated to zero by stopping the vehicle (a so-called "zero velocity update", ZUPT), the position will remain precise for a much longer time.

Control theory in general and Kalman filtering in particular, provide a theoretical framework for combining of the information from various sensors – so-called data fusion. One of the most common complementary sensors used for aiding INS based systems is a satellite navigation system such as GNSS (GPS, GLONASS, GALILEO).

Dynamical Environment: It is a big difference to operate an inertial measurement system in static lab conditions or low dynamic environment or in the "real-world". Check the performance of the IMS (IMS = **i**nertial **m**easurement **s**ystem) for the environment you want to operate the system in.

- Will it be used on an aircraft (transportation aircraft, helicopter, drone or fighter?),
- or on a rail vehicle (surface or underground?),
- or on a passenger car or a truck or a tank,
- or on a naval ship, a ferry or a speed boat or on an underwater surveying vehicle,
- or inside of a missile or a torpedo,
- or will it be used e.g. in a drilling application or in pipeline surveying or in machinery guidance,
- or will it be used e.g. to aquire the field of gravity with high accuracy?

To support your needs as best as possible, you can send us the Inquiry Form, filled with your application related information:

https://www.imar-navigation.de/downloads/faq/enquiry_imar.docx **or**

https://www.imar-navigation.de/downloads/faq/enquiry_imar.pdf

Compare the conditions of the data sheets of the systems intended to be used and the conditions in your application:

- E.g. will GNSS be available in the way as it is assumed for the data in the data sheet of the system?
- What is the behavior of the system under coning motion, which is e.g. the typical motion for ship applications?
- How does the system's parameters influence the desired performance?
- What operation mode is required (free inertial navigation, aided navigation, surveying, ZUPT operation, control and guidance or something else...)?

Take into mind that, also if you only want to know the motion of one single axis (e.g. only roll angle), under dynamic conditions in general a three axes measuring system (3 angular rate sensors and 3 accelerometers) is required to achieve the specification of the application. In general it is not possible to calculate a single axis motion in multi-axes excitation (solution of a non-linear transformation differential equation based on quaternions or direction cosine matrix) with sufficient accuracy using a single axes gyro or using one high accurate gyro and two lower grade gyros.

The motion error due to scalefactor errors of the inertial sensors is always dominated by the lowest performance gyro installed. Therefore it is important that the implemented data fusion (as used e.g. in our iNAT systems) is able to estimate also those effects.

Take into consideration that a MEMS gyro (working on coriolis law using vibratory excitation) and mechanical gyros (DTG) show a so-called g-dependent drift, i.e. they produce a drift (angular rate offset) dependent on linear acceleration and environmental vibration influence. High performance ring laser gyros (RLG = ring laser gyros) and hemispherical resonator gyroscopes (HRG) as well as mid performance fiber optical gyros (FOG) do not show such g-dependent drift, while higher performance fiber optical gyros (FOG) also suffer due to physical reasons significantly from vibration impact and temperature gradients.

iMAR uses inside their systems all state of the art gyro technologies and performance classes from MEMS over FOG ad RLG up to HRG, dependent from the application requirements, operating a robust and real-time data fusion with more than 40 states to estimate and compensate most of the the residual errors and even aging effects of the inertial sensors.

Also further complementary sensors can be processed within the data fusion, like wheel sensor information (odometer, VMS), DVL (Doppler Velocity Log), magnetometer data (magnetic heading – be carefull with these sensors as they are strongly dependent on environmental impacts, which cannot be compensated due to physical reasons, if they are changing during the mission) or dual antenna GNSS.

Sensor Technology and Data Fusion:

Each inertial sensor technology has its specific advantages and drawbacks which have to be considered regarding the foreseen application and desired accuracy. Some sensor technologies come e.g. with a very high stability of sensor performance (e.g. ring laser gyros) while others are for instance very light weight and comparable cheap, but being affected by possible aging effects (like MEMS based sensors). Therefore the signal processing on system level (“data fusion”) has to take care for this. Therefore the iMAR data fusion is able e.g. not only to estimate inertial sensor offsets but also to compensate scale factor drifts and other effects in real-time (more than 40 states are estimated, compared to the classical and most common only 15 states).

Gyro Bias:

If the system operates unaided (without odometer/velocity or GNSS or magnetometer aiding or similar), the gyro bias indicates the increase of the angular error over time (in deg/h or deg/s). If the system is aided with speed information (e.g. odometer / wheel sensor or Doppler log), the roll and pitch gyro drift can be compensated in the measurement system by data fusion and the gyro drift mainly affects the heading accuracy over time. If the system consists of low drift gyros, also the true heading can be estimated using gravity and earth rate information (so-called north-seeking or gyro compassing).

If the system is aided with position information (e.g. GPS or GLONASS or GALILEO or e.g. by machine vision), also the heading drift can be corrected and true heading can be obtained (even with medium grade gyros), if the applied motion dynamics is sufficient, i.e. if the heading state is observable in the Kalman filter[1]. But of course the smaller the gyro drift the better all possible angular corrections and the longer the allowed time where the aiding information may be not present (e.g. GPS in urban canyons)!

If the system is operated in free inertial navigation mode, the gyro bias is responsible for the position and velocity error over time (so-called Schuler oscillation).

Gyro Scale Factor Error:

This is an indication of the angular error which occurs during rotation. E.g. with 300 ppm scale factor error (=0.03%) the angular error is in the area of 0.1 degree after a one revolution turn. With a ring laser gyro or hemispherical resonator gyro system with < 10 ppm scale factor error the angular error is less than 1 arcsec (0.0003 deg) if the rotation angle is 30 deg.

---

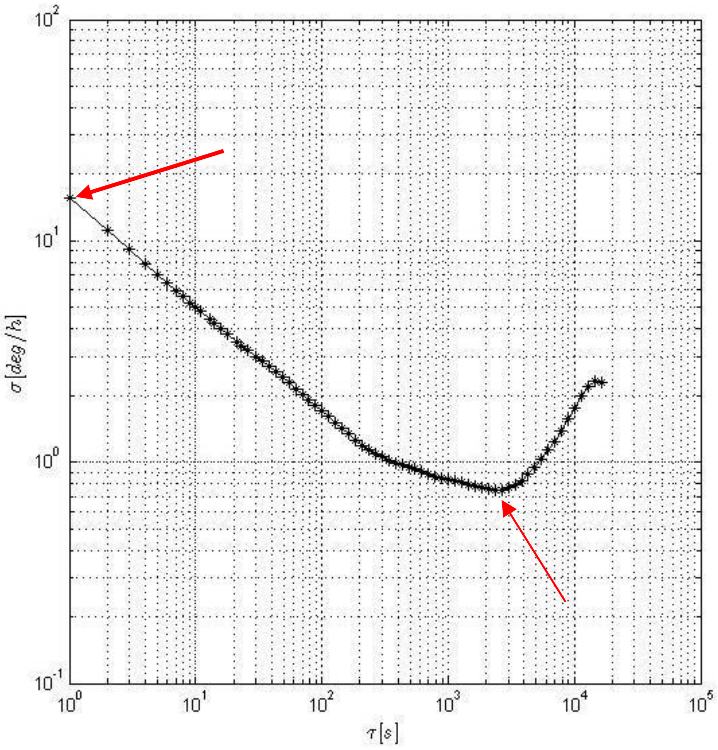
[1] Observability means, that the data fusion has enough information available to estimate certain states like gyro bias or heading. Example: If an aircraft flies always straight forward at constant speed, it is impossible to estimate vertical gyro bias or heading using a single antenna GNSS aiding, because due to the mentioned motion no significant acceleration or angular rate will be measured.

Misalignment: A misalignment between the gyro axes (or accelerometer axes) causes a cross-coupling between the measurement axes. A misalignment of 0.1 mrad inside of the system (e.g. residual calibration mismatch) leads to a roll error of 0.036 degree during a one revolution turn around the yaw axis (if the system is unaided). The smaller the required misalignment, the higher the requirements to sensor performance and calibration equipment (e.g. iMAR's multi-axes turn-tables).

Accelerometer Offset: An offset on an accelerometer leads to an error during alignment, i.e. determination of initial roll and pitch angle, because it has an direct impact on the accuracy of measuring the gravity g (approx. 9.81 m/s²) . An offset of 0.1 mg leads therefore to approx. 0.006 degree angular error in pitch or roll (0.1 mg = g x sin (0.006 deg)). The sensor offsets can be estimated during operation by the system due to the integrated Kalman filter data fusion, using GPS or DGPS data or ZUPT (zero velocity update procedure) if sufficient motion dynamics is available.

Bandwidth: In general the dynamic performance of an inertial measurement system is as better as higher the internal sampling rate and the bandwidth of the inertial sensors is. Also the proper internal data synchronisation (time stamping) is very important for accurate signal processing, not only if the IMS is operated under difficult dynamical environment. A high precision internal time reference and hardware based time stamping of all data therefore is very important for an INS with good performance reliabilty. Additionally a low latency of the data output is mandatory to use an INS for the trajectory or attitude control, e.g. of autonomous vehicles.

Gyro Random Walk: This value, given in deg/sqrt(hr), shows the noise of the used gyro. The larger the value the more noise is measured on the angular rates and on the angles. Some manufacturers also specify it as the noise density in deg/h/sqrt(Hz). Both values are equivalent for white white noise gyro output - if the second value is divided by 60, you get it in deg/sqrt(hr). An angular random walk of 0.003 deg/sqrt(hr) indicates, that the angular error (incertainty) due to random walk is e.g. 0.001 deg after 6 minutes (unaided) or 0.0004 deg after 1 minute (all values one sigma). The angular random walk is very important for the accuracy of north seeking, because if the random walk decreases times 2 then the needed duration for north seeking decreases by times four (if the resolution of the gyro is high enough).



The plot of the Allan Variance shows the square-root ARW of a MEMS gyro graphically (take the value at 1 sec and divide it by sixty to obtain the ARW in [deg/sqrt(hr)]).

At 1 sec the value of the square-root of the AllanVariance is 15 deg/hr. This leads to a value of the Angular Random Walk (ARW) of 15/60 deg/sqrt(hr) = 0.25 deg/sqrt(hr) = 0.0042 deg/s/sqrt(Hz) = 15 deg/hr/sqrt(Hz) [white gyro noise assumed]. The bias stability (minimum point of the graph) is 0.8 deg/hr at a correlation time of 3'000 seconds. So it is really quite a good MEMS gyro which we have in use.

Position error of an *unaided* INS:

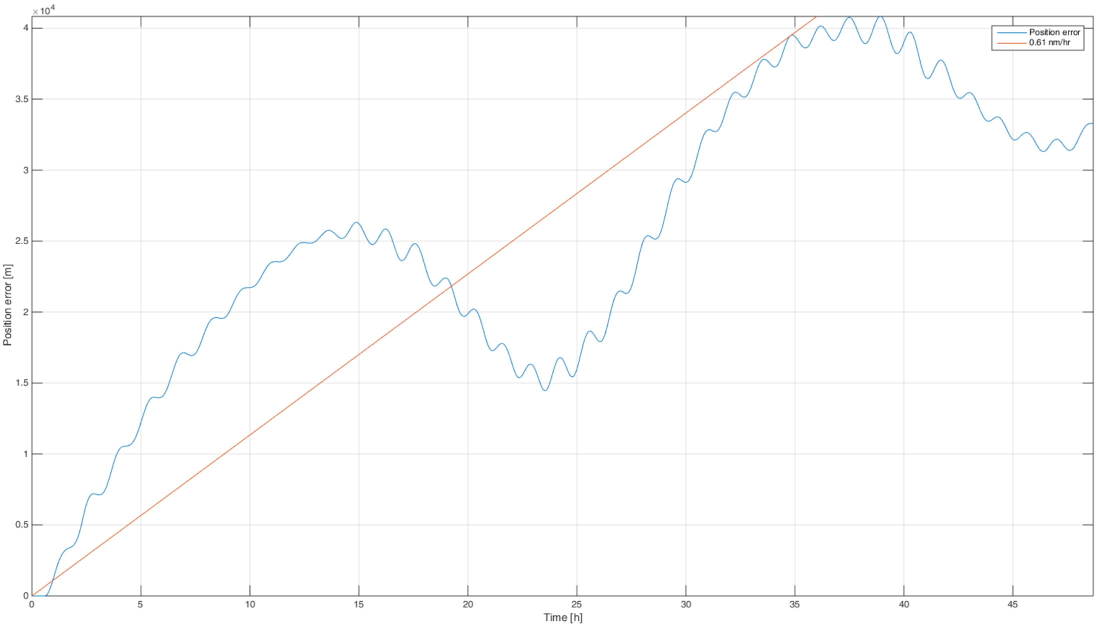
We have to distinguish between short-time accuracy and long-time accuracy of an **i**nertial **n**avigation **s**ystem (INS).

Long-time accuracy of an unaided INS:

This value (e.g. given in nm/hr i.e. nautical miles per hour) gives the global position error of an INS due to accelerometer errors and gyro errors, if the system is driven in a so-called Schuler loop operation (free inertial). Then the position error oscillates with a period duration of approx 84 minutes as well as with a period of 24 hours. The amplitude of oscillation depends on the accelerometer offset and the "shift" (avarage of position drift) depends on gyro drift (simple model assumption; details can be seen from the inertial differential equations!).

The following figure shows such long time behaviour of a free inertial navigation (example: data obtained from iNAT-RQT-4003 over more than 2 days):

The position in this plot is given in meters and the time in hours. As an example, the free inertial running INS shows a position error of 34 km after 48 hours (i.e. 0.4 nm/hr) and during this time the maximum error does not exceed 40 km. The error after 10 hours is about 22 km, the drift is about 1.2 nm/hr.



To improve the long-time performance of position determination without aiding (no GPS, no odometer!), the system can be set to zero-velocity all x minutes (ZUPT, zero velocity update). During this stand-still period, which may take 10 seconds all 3 minutes (example), the Kalman filter is able to estimate the internal sensor errors of the gyros and accelerometers and can improve the position performance dramatically (e.g. position error over 70 km distance with iNAT-RQH-4002 has been shown to be 3 meters as an example).

Short-time accuracy of an unaided INS (free inertial navigation):

These values (given in m or m/s) are relevant for measuring over durations less than approx. 20...40 minutes, because Schuler oscillation is not really relevant for short time measurements. An accelerometer offset leads to an position error increasing quadratically over time

delta_s = 0.5 x delta_a x T^2 [m] (a)

with delta_a = accelerometer offset [m/s^2] and T = measuring time [s].

Example for a medium accurate system:
delta_a = 1 mg ≈ 0.01 m/s^2, T = 100 sec ➔ delta_s = 50 m

The gyro drift delta_omega affects the position error corresponding to the equation

delta_s = g/6 x delta_omega x T^3 [m] (b)

with delta_omega in [rad/s] and g = 9.81 m/s^2 .

An attitude (roll/pitch) error of e.g. delta_attitude affects the position error due to a wrong compensation of the gravity on the horizontal IMS axes:

delta_s = 0.5 x g x sin (delta_attitude) x T^2 [m] (c)

Example, how you can validate manufacturer's statements (with data from a vendor's datasheet):

If someone promotes an IMS with 0.005 deg roll/pitch accuracy and advertises a horizontal position error of 0.7 m (and a vertical position error of only 0.5 m) after 300 seconds in free inertial navigation mode (i.e. without odometer aiding, without ZUPT; without internal vibration isolators), you can just check and calculate two things with the simple thumb rule equations given above:

- Position error due to 0.005 deg roll or pitch error after 300 sec (free inertial): 0.5 x 9.81 m/s^2 x sin(0.005°) x $(300\ sec)^2$ = 38 m (from equ. (c))

- What must be the accelerometer accuracy to achieve 0.7 m after 300 sec (free inertial)?
  0.7 m / (0.5 x $(300\ sec)^2$) = 1.5 µg (!!) absolute accuracy over 300 sec (from equ. (a))

The easy calculation shows the mismatch of the announced performance data (i.e. position error must be much worse or attitude error must be much smaller to achieve the advertised performance). For information: An absolute accuracy of accelerometer bias of 1.5 µg is close to gravimeter accuracy but not reliable available in industrial or military land navigation systems. Consider, that already the gravity by itself changes by about 0.3 µg per height meter !

Position error of an *aided* INS:

If the INS is aided, we have to distinguish between position aiding (e.g. by GPS/GLONASS) and velocity aiding (e.g. by odometer/wheel sensor or GNSS Doppler velocity or Doppler log).

Position aiding:

The INS provides high accuracy during short time periods while it shows significant position drift over long-time measurements. GPS e.g. provides position information with high noise and low data rate, but the position error does not increase over measuring time.

Therefore, using a Kalman filter approach for data fusion, the short-time accurate INS can be coupled with a long time accurate (complementary) position / velocity reference system (e.g. GNSS). iMAR's Kalman filter has typically not to be adapted to specific applications, but iMAR's architecture allows this, if required (e.g. to add additional states for additional constraints, parametrization of covariances, stability analysis etc.). In such applications of INS/GNSS coupling, the position will be provided due to the short time accuracy of the inertial sensors with excellent so-called neighborhood accuracy, while the global position error can never be better than the global position error of the position aiding system (e.g. GNSS). E.g. if GPS shows a constant position error over a longer time, also the INS/GNSS solution will follow those position error. But using different sources of aiding (GPS, ZUPT, odometer) the total position error can be minimized.

Velocity aiding / Dead Reckoning:

If velocity is provided for aiding (e.g. from a wheel sensor / odometer or from Doppler velocity log) instead of position, the position error of the total Kalman filter based data fusion will grow mainly with the scale factor error of the velocity aiding sensor. If e.g. GNSS aiding is present for a certain time before it will be interrupted (e.g. before the vehicle enteres a longer tunnel), the GNSS data will be used together with the IMS and odometer data to estimate the scale factor of the odometer precisely and automatically (together with some other installation parameters like mounting misalignment errors). This also allows to determine the position of the vehicle during long outages of the GNSS signal with high precision. As an example, using an iNAT-M200/SLN (MEMS based IMS) with wheel sensor, GNSS aiding and integrated data fusion, the position error after 10 km GNSS outage had been demonstrated to be typically about 8 m (i.e. < 0.1 %).

True Heading:

The "true heading" performance of an IMS is always an important parameter. If the IMS contains high performance gyroscopes (drift < 0.1 deg/hr), it can perform an autonomous gyro compassing, i.e. it measures the earth rotation rate, determines the levelling by measuring the gravity vector and calculates from these data the true north (heading) beside of roll, pitch and other values.

If the IMS does not contain such high performance gyroscopes, it can obtain the true heading only from a combination of a position reference (e.g. GNSS) and the inertial sensors, assuming sufficient motion dynamics to be present.

Using only GNSS (without inertial sensors), a so-called "track over ground" can be determined, which is obtained from the GNSS velocity in East and North direction, i.e. $\mathrm{atan2}(v_{east}/v_{north})$. Of course, this information shows only the direction of the motion of the GNSS antenna over ground, but it says nothing about the true heading of the vehicle (i.e. the direction of the vehicle's "nose")! Hence with a single GNSS antenna and without additional inertial sensors and without sufficient motin dynamics it is not (!) possible to determine the true heading.

Using a dual antenna system (as iNAT-M200/SLN-DA or iDAGOS) as stand-alone solution, true heading can be determined as long as both antennas can observe the same (!) GNSS satellites over sufficient time. GNSS outages can be bridged by the gyros – i.e. the better the gyro performance, the longer the duration of acceptable GNSS outages.

Conclusion: If the IMS contains inertial sensors with drift > 0.1 deg/hr and only a single antenna GNSS receiver (standard setup), it is easily possible to determine true heading with iMAR's real-time signal processing, but this requires two constraints (subject of physical laws):

a) The vehicle has to be under translatorial motion, and

b) The vehicle has to perform sufficient changes in heading to provide enough observability to the Kalman filter based data fusion to be able to estimate true heading with sufficient accuracy

An IMS without gyro compassing capability and without dual-antenna GNSS aiding is not able to determine true heading of its carrying vehicle, if the vehicle is moving only on a straight line without changes of direction (this feature is called as “lack of observability”). As soon as a change of heading occurs, the observability is given and the system can provide the desired information. It is very important to take this into account when selecting the right IMS/GNSS solution for the foreseen application (therefore it had been explained in this document extensively).

Time Stamping / Synchronization / Latency / Jitter: Especially if an IMS shall be used for control tasks or for surveying applications, a superior time stamping of the inertial data, odometer data and all other aiding information (GNSS, machine vision) is mandatory. Therefore iMAR’s measurement systems provide timr stamping with very high performance.

Example: If a target is moving with 100 m/s, a timing error of 1 milli second would already lead to a position error of 10 cm. Consider an RTK aiding with about 1 cm accuracy and you may immediately imagine why a synchronization accuracy with at least 25 µsec is mandatory together with a very high internal clock performance. Optionally INS being designed for advanced applications can provide NTP or PTP data for time synchronization and sometimes the integration of an semiconductor based atomic clock might be helpful when operating long time in GNSS denied environment.

Using an INS for control tasks, like autonomous vehicle guidance, a small latency and a small jitter of the acquired data as well of the data output is mandatory. The architecture e.g. of iMAR’s iNAT / iPRENA / iCOMBANA / iSULONA / iTraceRT-MVT / iATTHEMO systems also guarantee here best-in-market values.

EMI / EMC Protection: Inertial measurement systems for military or aviation use come with high EMI/EMC protection levels.

The systems being manufactured by iMAR are designed for the markets of surveying, vehicle testing, aerial laser scanning, pipeline instection, vehicle and camera stabilization etc. Due to the wide application area and strong reliability needs, iMAR systems are mostly protected and qualified according to strong standards like MIL-STD 461 and MIL-STD 704 or DO160 (beside of the environmental qualification according to MIL-STD 810). This prevents the system from unexpected electro-magnetic interferences and related performance degradation. Due to our high qualification level, about 50 % of all iMAR systems are also used within advanced military applications.

Check the protection level of the system, which you want to apply, against these requirements too. Especially inertial measurement systems being offered for commercial or surveying applications only, sometimes do not provide a sufficient EMI/EMC protection level and this may lead to operational problems in real world’s environment.

Open Interfaces: Open interfaces are very important for the user to have highest flexibility in using the system. Interfaces are user-interfaces as well as interfaces to external sensors like optional GNSS engines, odometer, depth/altitude sensor, visual odometry, DVL etc. The system's architecture should also provide custom specific interfaces if required.

GUI / Wizard: Users, which are new in the are of operating an inertial measurement system, sometimes need assistance to implement the system in the best way. For this typically a GUI is provided to configure the IMS on the vehicle.
Beside of configuration assistance such GUI should also allow a visualization of the acquired data in real-time as well as in playback mode.
Additionally an installation wizard is helpful to support the operator surveying the lever arms between GNSS antenna, odometer, camera etc. and the inertial measurement unit.
Last but not least such GUI should provide some maintenance features to allow even a fast system analysis in the field.
As an example you can see the recommended features of such GUI here: iXCOM-CMD

Also a lot of other features have important influence on the performance of an inertial measurement system. If you have additional questions please do not hesitate to contact us for further information.

Please don't hesitate to contact our support and sales engineers for any further questions!
sales@imar-navigation.de

Additional information can be found on our download site at www.imar-navigation.de

iMAR Navigation GmbH
Solutions in Inertial Navigation & Control
Im Reihersbruch 3
D-66386 St. Ingbert

Inertial Measuring Systems ***Made in Germany***

Phone: +49-(0)6894-9657-0
Fax: +49-(0)6894-9657-22

sales@imar-navigation.de
https://www.imar-navigation.de