New Approaches in
High-Performance Navigation Solutions for AUVs and ROVs

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High-performance AUVs used in surveying or service-and-maintenance applications require the most accurate navigational information to fulfil their tasks with the greatest economical and technical efficiency. But underwater navigation requires different solutions than common in aircraft navigation or land vehicle navigation applications.

The use of inertial measurement systems in underwater vehicles may have three goals:

1. Determination and stabilisation of roll, pitch and heading of ROVs and AUVs to improve the operational behaviour of the vehicle
2. Position determination of the vehicle to know the location of the ROV in real-time
3. Navigation, guidance and stabilisation/control of the AUV

A navigation system for AUVs typically consists of several components. The dynamical state (angular rates, acceleration in three-dimensional space) as well as the atti-

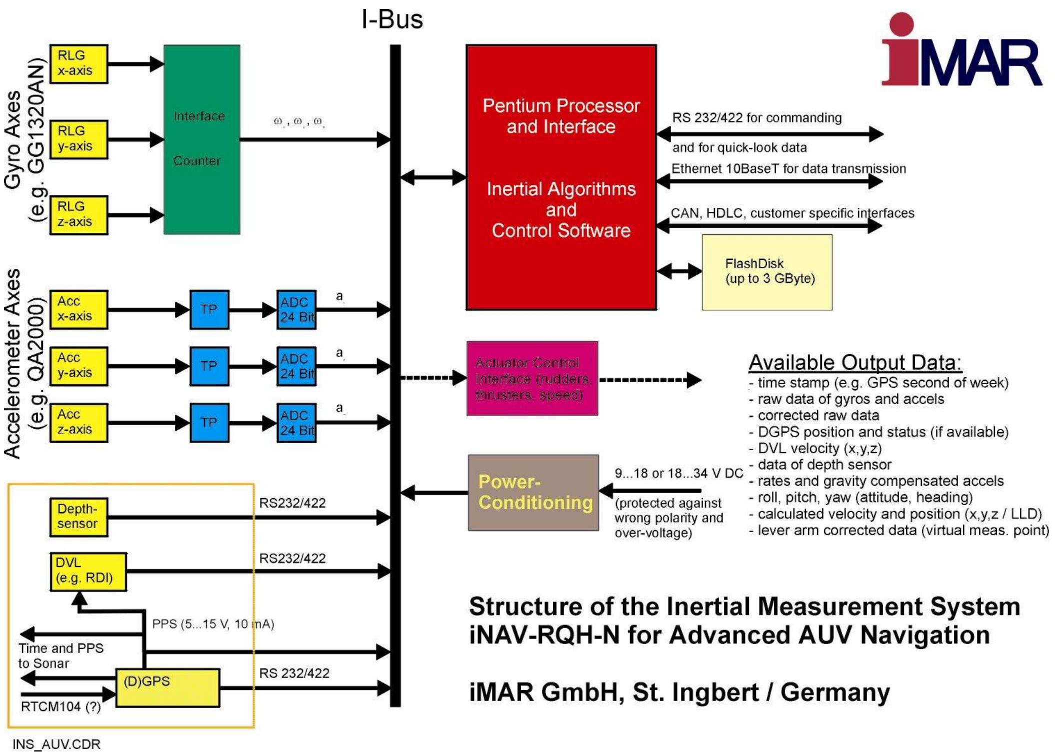

Figure 1: Structure of iMAR's inertial measurement system for AUV applications

tude and heading can be determined by an inertial measurement system, which in its basic form contains three angular rate sensors (commonly called gyroscopes, although in optical "gyros" there is no rotating part inside!) and three accelerometers. But using only these inertial sensors to determine the position by double integration of the gravity-corrected acceleration would not be successful for AUV navigation requirements and would lead to position errors increasing dramatically over time. Additionally, the well-known procedures of inertial signal processing, such as Schuler tuning or zero velocity update, would not be successful in AUV applications due to the large oscillation of the position error of some nautical miles (nm), and the average position error would be in the area of 0.5 nm m after 24 hours with the best inertial measuring systems used, for example, on atomic submarines. Furthermore, of course, those navigation systems are not applicable on AUVs.

Therefore, additional aiding sensors such as Doppler Velocity Log (DVL) and pressure sensors are used to get additional information about speed and depth. With such system configurations, residual position errors of a few meters per hour can be achieved. This navigation principle is called "dead reckoning navigation". Figure 1 shows a block diagram of a navigation system capable of working in free navigation mode as well as in dead reckoning mode.

The following demands made of the navigation unit are typically for advanced AUV applications:

- Highest accuracy in heading, roll, pitch and position for stabilisation of sensors and tools moved on AUV-mounted robotic arms.
- Short alignment time, even under difficult dynamical conditions, i.e. autonomous north seeking.
- Advanced Kalman filter approach for INS/DVL/GPS data fusion.
- Open interfaces for external aiding devices such as Doppler velocity log (DVL), acoustic positioning system (APS), GPS, pressure sensor, etc., and output of an integrated navigation solution as well as the possibility of connecting the actuators (rudders, thrusters) of the AUV/ROV to control the vehicle globally or locally, if desired.
- Flexible design of the navigation system with the option to realise it in a customer-specific design (e.g. integration of DVL and INS in one single housing)
- Availability of a range of navigation systems from medium performance (dynamical stabilisation of ROVs, e.g. iVRU-FAS-C167) up to ultra high performance (e.g. iNAV-FJI-N or iNAV-RQH-N for autonomous long-term operation tasks of AUVs)
- Open user interface to allow the user to control all features of the navigation system. Hardware interfaces supported by the navigation system will be CAN, Ethernet, RS232, RS422, etc.
- Availability of navigation systems of different classes of accuracy with the same interface structure to make it as easy as possible for the user to operate different classes of AUVs and ROVs in his fleet without changing interface software or interface hardware.

Over a long time, for instance, the NATO Saclant Center for Underwater Research in Italy was looking for the most accurate available inertial navigation system able to operate inside of an AUV for use with its SAS system (Synthetic Aperture Sonar). In this application, a lot of sonar patterns must be fitted together with highest accuracy in position, attitude, heading and velocity to achieve the desired resolution. The call for bids for the INS was published worldwide, and in the end, the iNAV-RQH-N system was selected (figure 2). It is a highly sophisticated small-size laser gyro-based inertial navigation system specially designed and manufactured by iMAR in St. Ingbert, Germany, for naval applications. iMAR is well known as a manufacturer of high-precision inertial surveying systems for the German Air Force (used in their SAR [synthetic aperture radar] systems). iMAR has developed the navigation systems for the German Navy's new heavy-weight torpedo DM2A4 as well as a lot of highly sophisticated inertial stabilisation tools for torpedo counter-measure devices. They have manufacturing lines for low-accuracy inertial measurement systems up to the most accurate navigation and motion reference systems (further information at www.imar-navigation.de). The measurement system selected by Saclant Center demonstrates an accuracy of 0.3

Figure 2: iMAR's Navigation System iNAV-RQH-N with gyro drift down to 0.002 deg/hr (reference: www.imar-navigation.de)

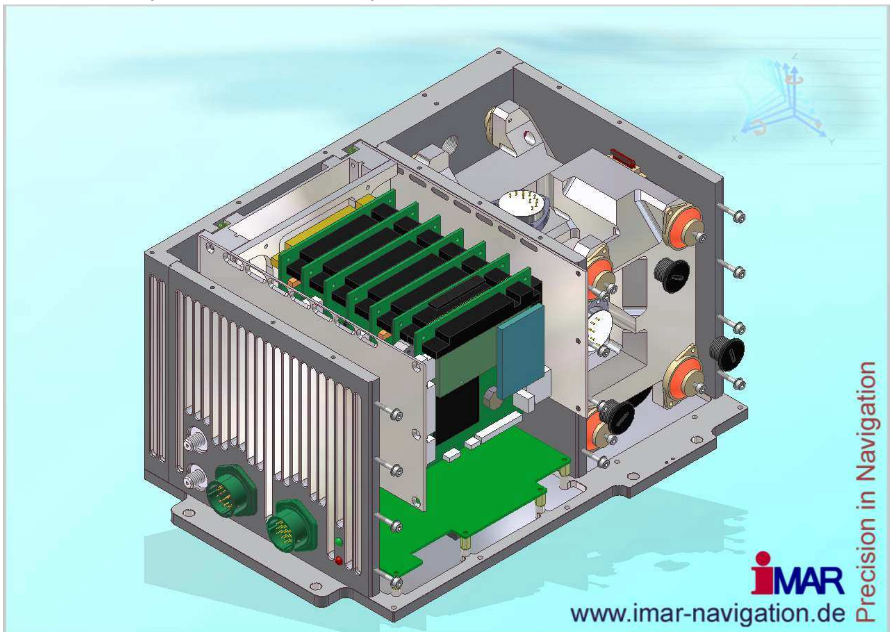

Figure 3: Sensor assembly with laser gyros and processor boards inside of iNAV-RQH-N

arc-min in roll and pitch and a short-time stability of better than 0.01 arc-sec per second. For this NATO application, it is very important to also have the most stable determination of the velocity and position available (only a few meters per hour position error allowed), which is achieved using a DVL manufactured by RDI.

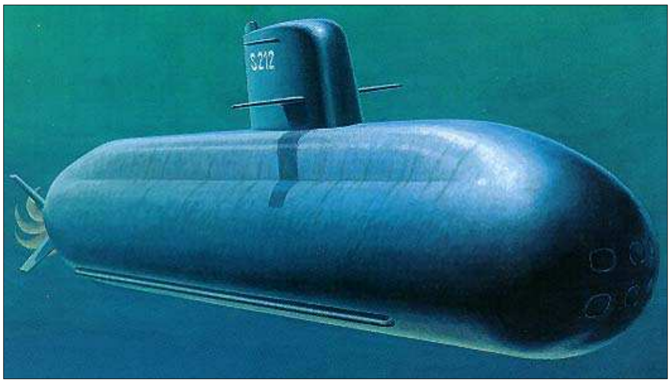

Figure 4: A deviation of the iNAV-FMS is used as an advanced torpedo AHRS in the new type U212 submarine.

With the SAS developed at Saclant Center, the detection and location/surveying of known and unknown objects on the seabed (search for old munitions, mines, etc.) is possible. The call for bids for the INS was published worldwide and won by iMAR, thanks to its extensive experience in high-precision inertial strapdown and stabilisation algorithms and its modular, open and reliable yet economical system design.

Another important project in advanced design and application of AUVs is a vehicle called "DeepC". DeepC, in development by Atlas Elektronik GmbH in Bremen, Germany, is perhaps the most flexible and modular system design of an AUV to this day and seems to have the potential to become one of the leaders in the market of high-performance AUVs. Its revolutionary concept in power management, payload administration and intelligent mission control will also allow the performance of applications which were not executable in the past. Recently, iMAR's iNAV-RQH-AUV also won the competition for this demanding application where accurate navigation is of utmost importance for the success of missions taking 60 hours over a distance of 400 km at depths of up to 4000 or 6000 m.

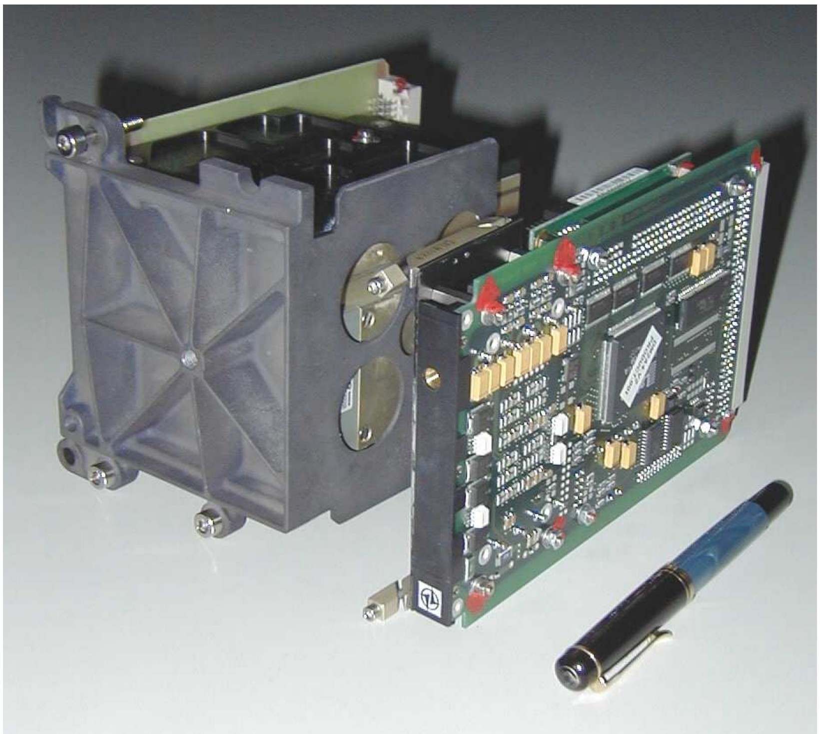

Figure 5: Open-frame-IMU of class 1 deg/hr for AUV applications

Key features of the navigation system for this application include access to all raw data of the INS so that the manufacturer of the AUV has the possibility inside of his central AUV control computer to model the dynamical behaviour of the vehicle for advanced thruster control. The navigation data of iNAV-RQH-N are available at up to 400 Hz and can be transformed to individual virtual measuring points (lever arm definition) to support high-accuracy docking or surveying operations, for example.

Figure 6: iNAV-FMS for advanced tasks of ROV stabilisation and guidance

Besides the applications for high-accuracy navigation solutions, many more applications need "only" stabilisation that will work under both static and dynamic conditions with high reliability and performance (so-called attitude-heading reference, AHRS).

The advantage of using an inertial measurement system with fibre-optic technology in strapdown technology is the high bandwidth, which allows high-efficiency control of the AUV at a reasonable cost. It can also provide very accurate dynamical heading, even where low bandwidth causes the master compass to have a strong time lag. In a UK Royal Navy application, for example, iMAR's iNAV-FMS was selected to provide roll/pitch accuracy with less than 0.1 degree deviation, even under difficult conditions such as so-called coning motion.

Figure 7: iNAV-FMS during burn-in at iMAR's inertial calibration facilities

The iNAV-FMS is a commercial deviation of iMAR's torpedo navigation system iNAV-FMS-T, which is in volume production for the German Navy and was created during the development of the new German Navy's type U212 submarine. The algorithms of navigation and stabilisation have been proven over several hundred nautical miles of operation. Acoustic reference systems (hydrophones) on the test field of the German Navy's test centre in Eckernförde were used to confirm the dynamical and long-term stability of the system.

While systems equipped with low-cost vibrating gyros will produce significant errors in these "real-world" conditions, the iNAV-FMS will not be affected by such motion influence due to its low gyro drift of as low as 1 deg/hr and its very low scale factor error of 300 ppm. The high scale factor error and gyro drift of a lot of low-performance systems available on the market today, which are equipped with vibrating or low-cost optical gyros, are responsible for such coning drift and are the reason why those systems often show disappointing results in a real dynamical environment.

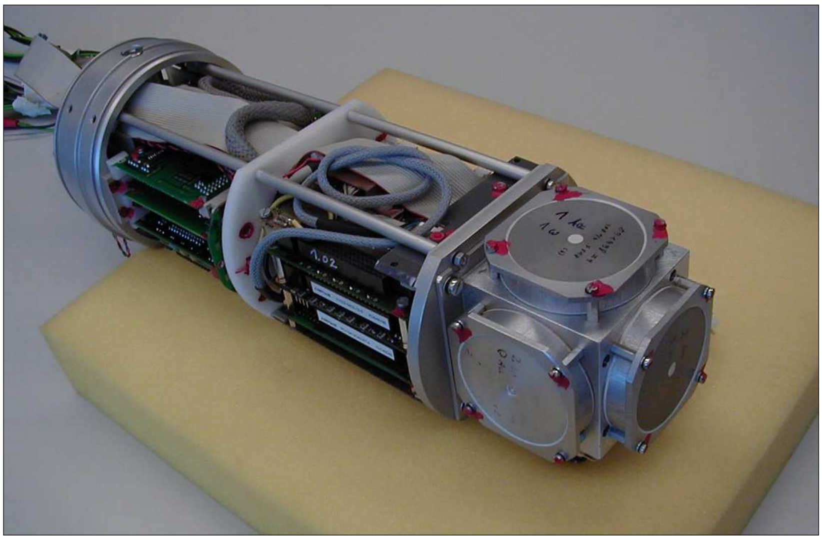

Figure 8: Stabilisation unit iNAV-FOS with open-loop fiber-optic gyroscopes (customized design, diameter 120 mm resp. 5")

It is important for the user of inertial measurement systems to compare the technical data of different systems on the market under the same conditions. What's very important is the knowledge of the error behaviour of attitude and heading under so-called coning motion, which is the typical motion excitation of surface and underwater vessels, and under change of heading during diving up and down. Ideally, the inertial measuring system should be a "black box" for the AUV integrator as well as for the AUV user, but the user has to have at least some basic knowledge of the operation principle to get a feeling for possible error sources and for the error budget of each navigation solution, such as acoustics, inertial navigation and the combination with the principle of dead reckoning. As an example, the position error of an INS inside an AUV must be analysed very carefully.

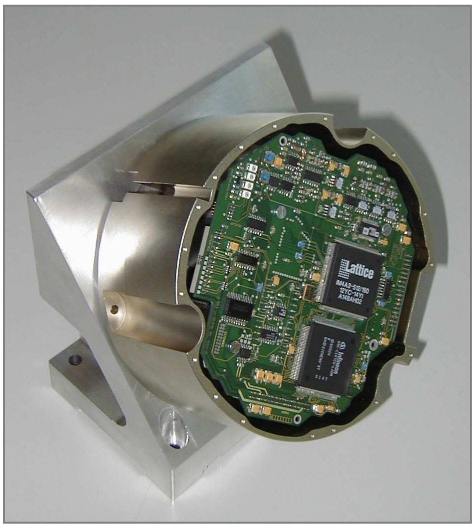

Figure 9: IMU for surveying and weapon control applications

Figure 10: Ruggedized small-size low-cost AHRS iVRU-FAS for AUV and platform stabilisation

Often, the position accuracy is demonstrated using test patterns where the INS errors and DVL errors compensate themselves. For example, riding a certain distance in northerly direction, making a 180° turn and coming back to the starting point shows excellent position errors at the end of the mission, because the DVL scale factor error is the same on both paths and thus compensates almost entirely. Therefore, it is important to look to the position after half of the distance is travelled. Or with a meandering trajectory, all scale factor errors of the heading gyro eliminate themselves. On the one hand, this shows how to design an AUV's trajectory to minimise influences from the navigation system, while on the other hand, the measuring conditions must be taken into account when comparing different navigation solutions.

Navigation systems as well as IMUs for stabilisation tasks are available on the market, but to make a proper and efficient system design for a special AUV solution, very deep knowledge about inertial navigation, acoustics and especially about optimal filtering like the design of application-oriented advanced Kalman filter solutions is required. And such solutions require a modular architecture of the navigation system with the possibility of cost-efficient adaptation to the individual AUV or ROV system design.

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iMAR GmbH, located in St. Ingbert in the Southwest of Germany, is a leading European manufacturer of inertial measurement systems for advanced applications, from space down to the demanding tasks of underwater navigation and guidance. The manufactured systems of iMAR's Naval Division, mainly based on fibre-optic gyro technology and ring-laser gyro technology, are running in several industrial and military underwater and surface applications from heavyweight torpedoes and underwater target simulators to high-accuracy helicopter landing path stabilisation on surface vessels and highly sophisticated AUV applications. Other operational areas of iMAR are the development and manufacturing of inertial measuring systems and application software for vehicle motion analysis, land navigation, navigation and stabilisation of RPVs, missile guidance, surveying systems for GIS applications, camera and antenna stabilisation systems on aircrafts, drilling systems, etc. (see also www.imar-navigation.de). In May 2003 iMAR moved to its new headquarters building providing additional 1,500 sqm facility for production, development, support and training.