# iMAR Navigation GmbH - Railway Systems and Solutions

iMAR Navigation GmbH, a company based in St.Ingbert/Saarbrücken, Germany, provides highly precise inertial navigation systems since 1993 and to the railway industry since 1998.

Products and solutions include but are not limited to the legacy iNAV and the current iNAT series as well as special units such as iRailLoc-C, iRad and iZET-Mobile (see below) series.


*Figure 1: iMAR products used in the railway industries (www.imar-navigation.de )*

## Railway Industry

iMAR products are used by a variety of customers in the railway industry. Notably iNAV and iNAT systems are used for highly precise localisation and attitude referencing e.g. for track and clearance profile measurements (Camera, **L**ight **D**etection **A**nd **R**anging (LiDAR)).

In the United Kingdom iNAV/iNAT systems are widely used by Omnicom Engineering, now Balfour Beatty Omnicom, for laser measurement and software monitoring systems and services.

### Deutsche Bahn AG

Deutsche Bahn uses inertial measurement systems of the iNAV-RQH-4003 series and its successor iNAT-RQT-4003 in the track measurement wagon RAILab and other measurement trains such as the advanced TrainLab and LIMEZ II / LIMEZ III etc. They have been certified by Deutsche Bahn with regard to their high accuracy.

*Figure 2: Deutsche Bahn AG, from left clockwise, iNAV-RQH-4003 on LIMEZ III train, iNAV-RQH-10018 on RAILab, iNAT-RQT-4003 on advanced TrainLab*

### Swiss Federal Railways (SBB), SmartRail 4.0

The Swiss Federal Railways (SBB) in 2015, while building the Gotthard Base Tunnel, with 57 km length the world's longest rail tunnel, tasked iMAR to implement an iNAT-RQT-4003 in the Radio Measurement Vehicle called «MeWa12».

Special inertial referencing methods were developed to minimise localisation errors (typically ~10 m after 57 km travel through the tunnel without any post-processing).

iNAT-RQT-4003 provides the location data to certify the safety critical rail communication system (GSM-R) used for signalling (ERTMS/ETCS) in the Gotthard Base Tunnel.


*Figure 3: SBB MeWa12 Telecom Measurement Train leaving the Gotthard Tunnel at the south portal*

Cooperating with Schild & Partner GmbH (SuP), an engineering company based in Vienna, Austria, iMAR was tasked by SBB to participate in advanced, safety critical localisation research & development during the SmartRail 4.0.

Within the SmartRail 4.0 programme prototypes such as the iZET-Rad (today part of iRAD series) and various localisation methods and algorithms (see below) were developed and field tested on the SBB rail network.

*Figure 4: SmartRail 4.0, iZET-Rad prototypes: InnoTrans 2022 with Schaeffler axle generator (left), iRAD mounted on SBB MeWa12 axle (right)*

In 10/2022, SBB, iMAR and Siemens Mobility agreed to equip a regular operating train of type DOMINO in Switzerland with iNAT-RQT-4003 as a ground truth reference and other equipment to collect and analyse relevant data for future ETCS level implementation. This train will also be used in international R&D projects.

### Austrian Federal Railways

In 2017 the Austrian Federal Railways (OeBB) requested iMAR to provide referencing systems based on iNAT-RQT and iNAT-M200. The systems are used for location referencing on OeBB railroad locomotives.

Furthermore, OeBB tasked iMAR to develop dedicated localisation systems for level-crossing safety and automated shunting operation.

Figure 5 shows an iRailLoc-C localisation device (integrated INS, GNSS, odometer, GSM-R) mounted on an OeBB shunting locomotive.


*Figure 5: iRailLoc-C (localisation (INS/GNSS/ODO/+) on shunting locomotive*

## Timing and Localisation Applications & Use Cases

In the SBB SmartRail 4.0, starting in 2018, iMAR broadened the product range in railway applications venturing from pure referencing to operational, safety critical components for signalling applications.

Building upon the experience in other domains, such as aerospace and automotive, iMAR provides sensor fusion-based localisation products and solutions, including advanced optical sensors including LiDAR, for various railway uses cases.

The following table outlines iMAR products and their relevance for typical railway use cases and applications.

| Use Cases | iNAT | iRailLoc-C | iZET Series | RAD Series |
|---|---|---|---|---|
| Timing & Localisation | x (referencing) | x | x | x |
| Train Speed | | x | | x |
| Train Length | | x (locomotive) | x (end of train)* | x (end of train)* |
| Train Integrity | | x (locomotive) | x (end of train)* | x (end of train)* |
| Vehicle Condition | | | x | x |
| Track Condition | x | x | | x |

** for this feature, iZET, mounted on the end-of-train plate holder of the last waggon (or iRAD, mounted on the axle of the last wagon), requires an iRailLoc-C or similar device on the locomotive for localisation of the head of the train.*

### Timing & Localisation

Today railway operation is event orientated such as a train passing a signal or occupying a certain space (a fixed block).

With the introduction of mobile communication (GSM-R) and the necessity to optimise flow and track usage exact timing and localisation becomes an essential operational requirement:

- implementing and certifying communication systems, see Gotthard Tunnel example, requires exact time and localisation referencing.
- operational signalling systems based on ERTMS / ETCS L2/L3 requires safe, real-time localisation.

Core functionalities of iMAR products are exact timing and localisation with high ac¬curacy, reliability and availability. Multiple sensors and sources are combined in sensor data fusion algorithms (e.g. Kalman Filtering) in precisely engineered products meeting all transportation, aeronautical and MIL-standards.

Thus accuracy, integrity and continuity are ensured throughout operational scenarios in most demanding conditions and environments.

Figure 6 shows some sensors and sources as they are used in iMAR railway systems and solutions.

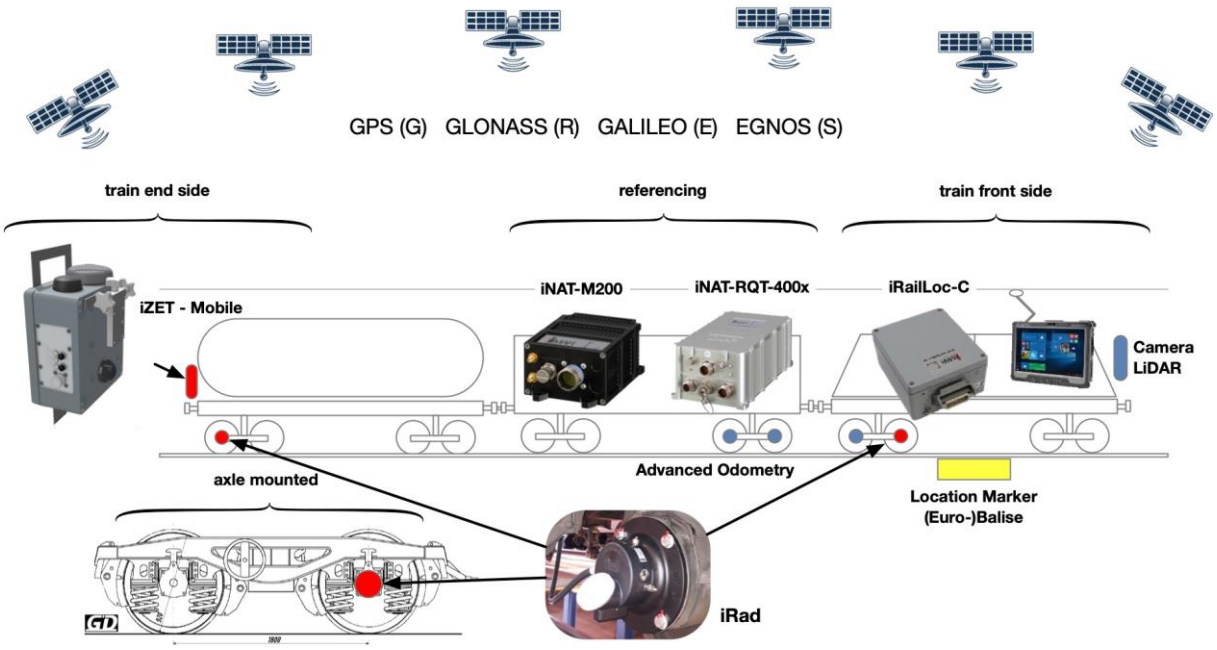



*Figure 6: Sensors and Sources used in railway systems and solutions*

## Train Speed

Train speed is primarily based on wheel tick measurements processed to wheel speed within onboard units. Combined with sensors, such as Doppler radar, odometry provides essential speed referencing to the vehicle driver and signalling sub systems.

Powered axles with friction and environmental conditions (rain, snow) induce errors and outliers in wheel tick measurements. A safety critical change request[1] recently filed by the Swiss Ministry of Transport addresses these issues.

Using inertial sensors and GNSS measurements together with a sophisticated signal processing, the iRailLoc-C but also the iNAT systems detect and mitigate wheel tick measurement errors and outliers.

Figure 7 shows results from the SmartRail 4.0 Proof-of-Concept (PoC). iNAT systems improve highly precise wheel odometry of the SBB Mewa12 Telecom measurement vehicle by about a factor 2 resulting in an error of 0.05% for 5 km distance travelled.

[1] CH-TSI CCS-038, «Offenbarung bei grosser Aufweitung des 1.1 Odometrie-Vertrauensintervalls», ERA ERTMS ID CR1389

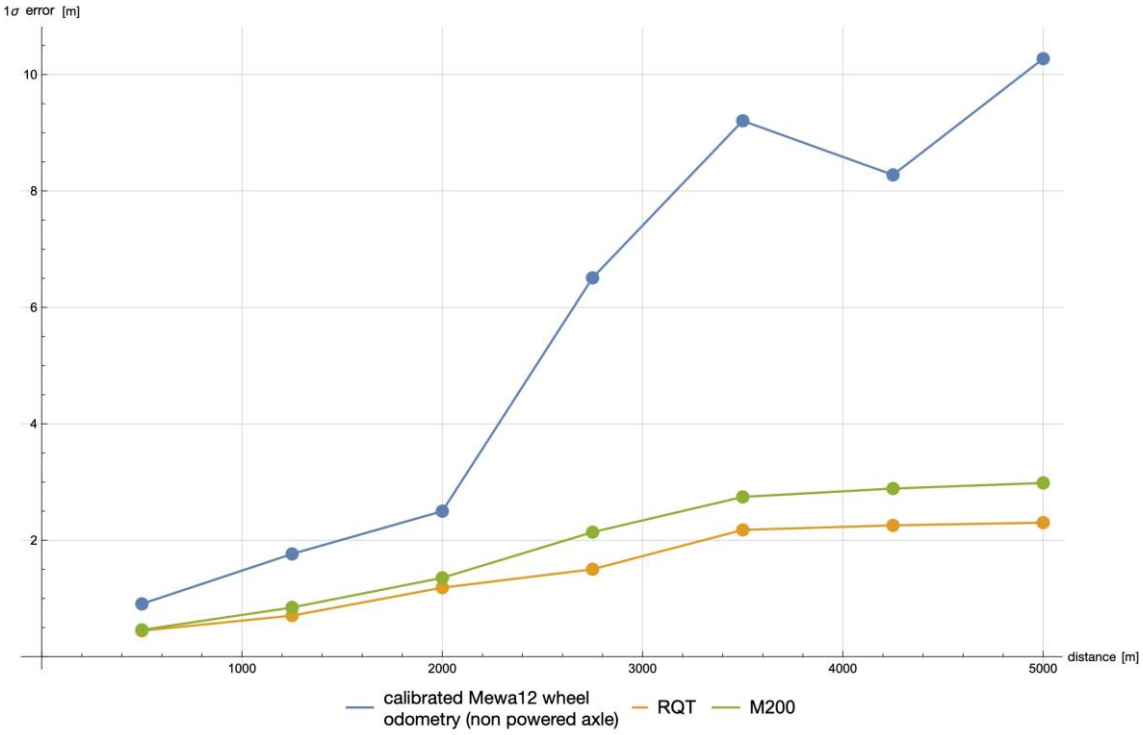



*Figure 7: Improvement of wheel based odometry using iNAT systems*

Safe and accurate train speed is essential for automated, flow optimised operation while minimising signalling infrastructure.

### Train Length & Integrity

ERTMS ETCS L3 and moving block operations knowledge of train length and ensuring train integrity are essential requirements.

iZET-Mobile is a train-end mounted device which in combination with train front side localisation, iRailLoc-C, enables train length determination and train decoupling detection.

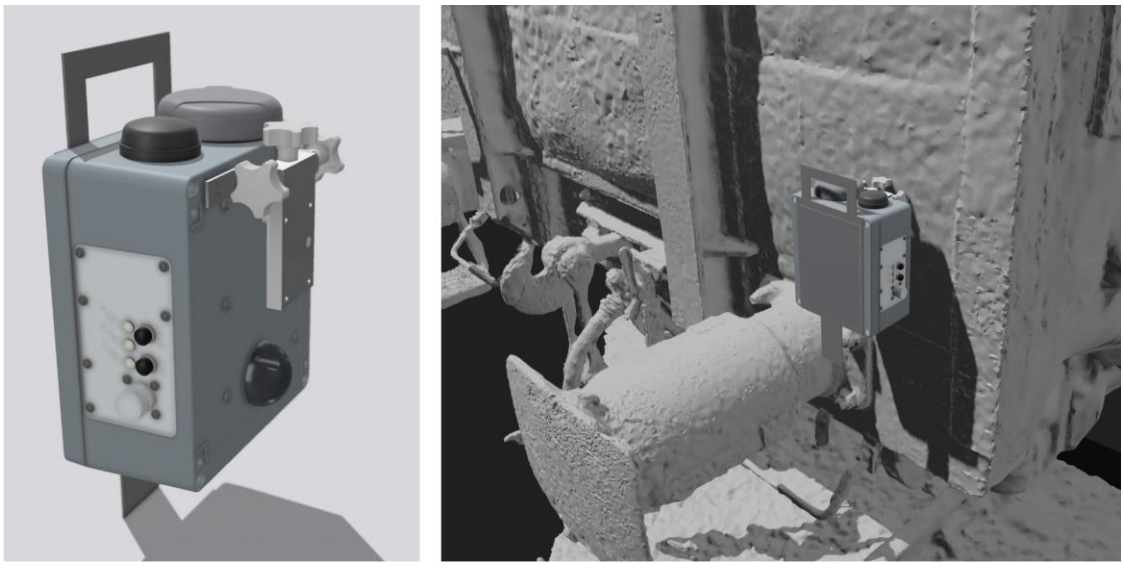


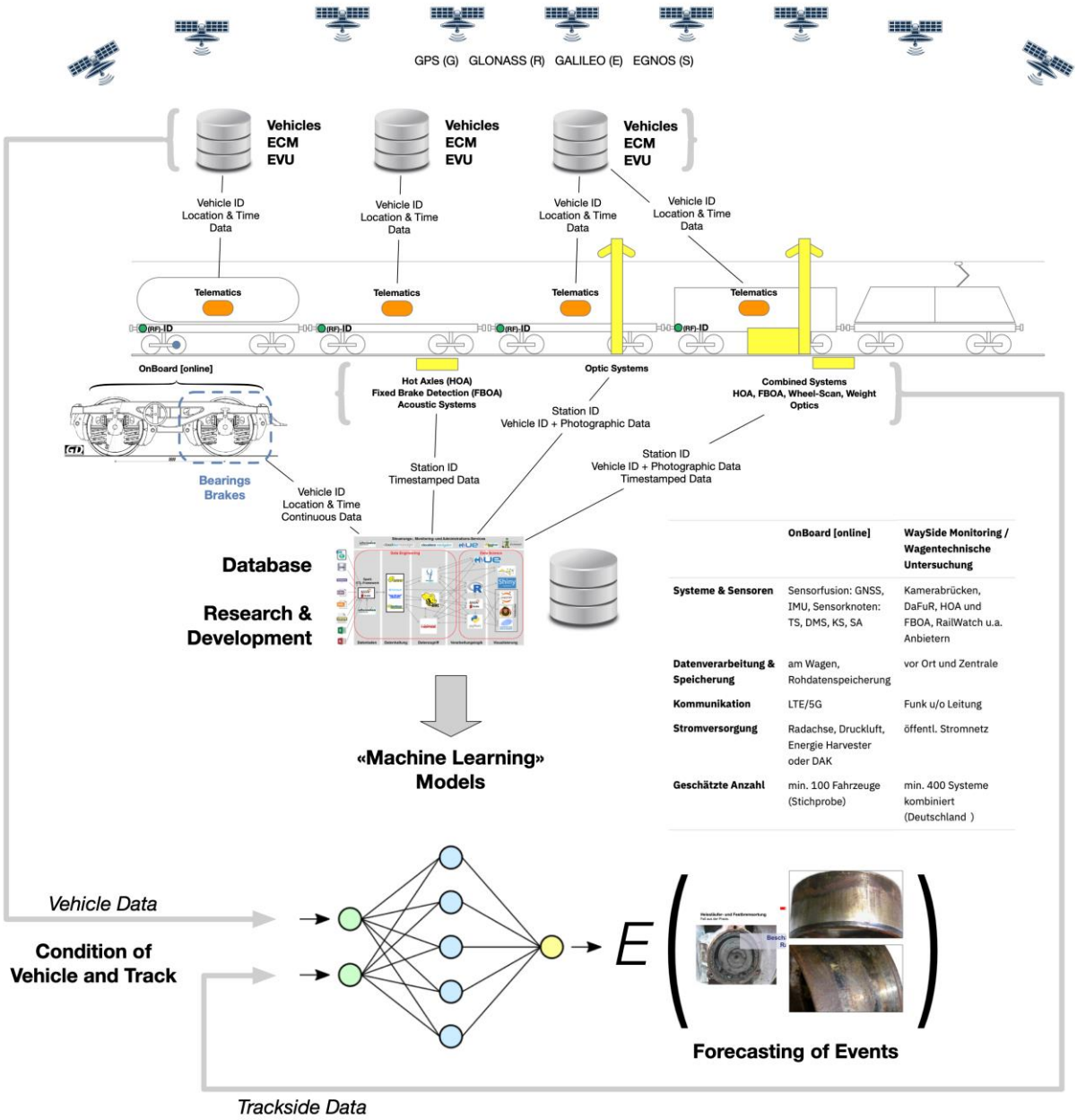
*Figure 8: iZET-Mobile model (left) and mounted instead of tail disc (right, scanned model)*

## Vehicle Condition Monitoring

In cooperation with industrial partners on behalf of the German Ministry of Transport iMAR managed and authored a study addressing methods of monitoring the vehicle state, condition and mechanical components (axles, brakes, a.o.) of cargo vehicles.

The study results are available on request or in German language.[2]

Figure 9 shows an overview of the proposed vehicle state monitoring system setup. In essence within the system data is collected from different sensors and systems mounted on vehicles and along the tracks. Using this data in combination with forecasting and artificial intelligence vehicle states and component health status such as axles, brakes, structure, a.o. can be predicted. Thus, operational safety, e.g. preventing derailing accidents, and scheduled maintenance can be improved significantly.




[2] https://www.dzsf.bund.de/SharedDocs/Textbausteine/DZSF/Forschungsberichte/Forschungsbericht_2022-26.html?nn=2203708

*Figure 9: Determining vehicle state with sensors and systems*

The axle mounted devices iRAD but also the waggon or locomotive mounted iNAT and iRailLoc-C systems can be used to collect vehicle data in real-time. iMAR provides both, expertise in data processing including forecasting and artificial intelligence systems as well as design and manufacturing of most ruggedised hardware solutions.

## Track Condition

During the SmartRail 4.0 programme in cooperation with Schild & Partner GmbH algorithms to determine track states were developed and field tested on the SBB track network.

Using an iNAT-M200 INS/GNSS/ODO based system mounted on the SBB Telecom measurement vehicle track properties such as track radius, cant and gradient are precisely reproduced as heading, roll and pitch movements of the M200 unit.

Figure 10 shows an example of a track section (green line).

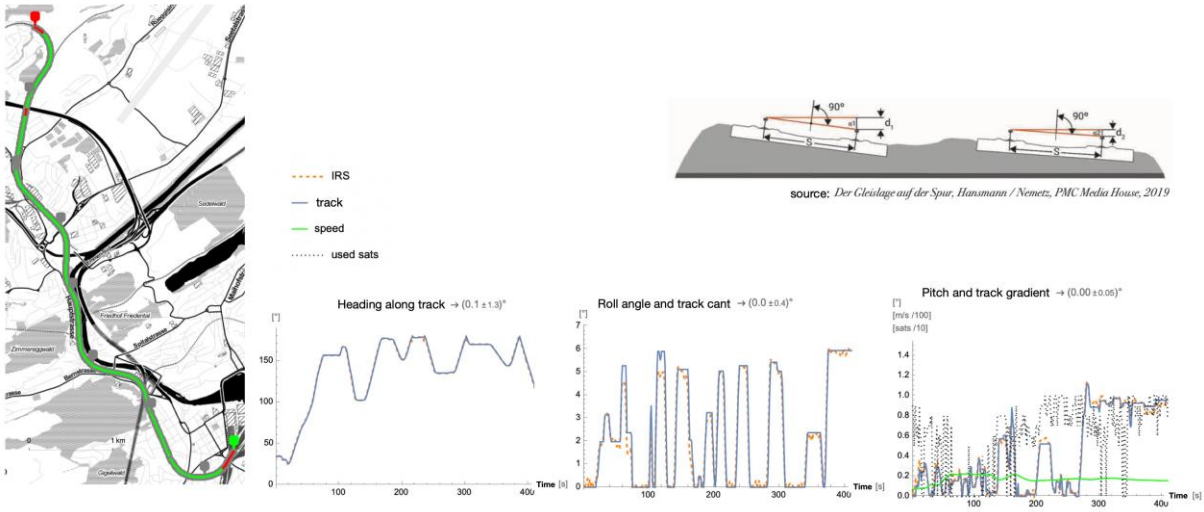



*Figure 10: Track states such as track cant and gradients from iNAT measurements*

In addition to dedicated measurement vehicles also normal operating rolling stock equipped with iMAR products may be used to collect track state data. When used in forecasting models and employing predictive maintenance this data enables infrastructure operators to improve track utilisation and save cost.

For determining and modelling track state iMAR provides sensors, such as the iNAT, iRailLoc-C and iRad series, as well as algorithms and solutions.

## Products & Solutions Overview

iMAR is a vertically integrated engineering and manufacturing company. It designs, develops and manufactures hard- and software including algorithms, all in-house, *Made in Germany*.

*Figure 11: iMAR Navigation GmbH - Engineering, Manufacturing, Quality*

Depending on customer requirements iMAR combines a wide range of sensors. That could be low-cost **M**icro-**E**lectro-**M**echanical **S**ystems (MEMS) up to highly precise Ring Laser Gyroscopes or aviation grade single-frequency L1 Navstar **G**lobal **P**ositioning **S**ystem (GPS) receivers up to highly accurate **R**real **T**ime **K**inematic (RTK) Multi-Frequency Multi-System **G**lobal **N**avigation **S**atellite **S**system (GNSS) from a variety of vendors, always selected ac¬cording to the foreseen application and environment.

Components are integrated into high quality, robust in-house designed structures. Required **E**lectro**M**agnetic **C**ompatibility (EMC) testing is also done in-house (see figure 12) according to railway and military standards. Through software and algorithms systems are fine tuned for top-of-the-line performance.

*Figure 12: iMAR EMC facilities at Special EMV, located at iMAR Campus in St. Ingbert, Germany (www.spezial-emv.de)*

### Inertial Navigation (iNAV) and Core Navigation and Timing (iNAT) Series

These are top-of-the-line systems used for navigation, guidance and control of vehicles, stabilisation of platforms, surveying reference as ground truth etc. in the fields of industrial, automotive, surveying, research and space applications. Developed for rugged industrial applications according to MIL standards, they are used also for major defence applications as well as for aviation and railway use cases due to their exceptional robustness and reliability.

The iNAT-RQT-400x, for example, is a family of light weight small-size high accurate advanced RLG based INS of class < 0.004 deg/hr / 70 µg, consisting of 3 airborne grade ring laser gyro axes and 3 servo accelerometer axes, integrated up to all-frequencies GNSS Receiver (GPS, GLONASS, GALILEO, BEIDOU), up to three wheel sensor interfaces and an advanced 42+ state Kalman filter based INS/GNSS sensor data fusion (loosely or tightly coupled).

iNAT series products are used for navigation, guidance and control of vehicles, stabilisation of platforms, surveying reference as ground truth etc. in the fields of industrial, automotive, railway, mining, sea and subsea, surveying, defence and space applications.

| | |
|---|---|
| Applications: | GNSS aided navigation, free inertial Navigation (air, land, sea, subsea), attitude heading reference (AHRS), surveying, UAV, AUV and RPV guidance & control |
| Real-time data output: | longitude, latitude, altitude / height, velocity, roll, pitch, yaw / heading, angular rates, acceleration, status, calibrated raw data INS/GNSS (for post-processing) |
| Interfaces: | RS485 (UART and HDLC / SDLC) Interfaces, CANaero / ARINC825 / CAN, ARINC429, Ethernet (TCP/IP and UDP), SYNC-I/Os |
| Characteristics: | Data Output rate up to 300 Hz (each data log separately adjustable)<br>Minimum latency and minimum jitter on data output<br>Measurement range +/-400 deg/s, +/-40 g<br>Heading accuracy 0.015 ... 0.05 deg sec lat<br>Attitude accuracy < 0.005 ... 0.02 deg<br>Position accuracy free inertial 0.2 ... 2 nm/hr<br>Position accuracy GNSS aided < 1 m (rms) [S/A off]<br>Position accuracy GNSS aided 0.02 m (rms) [RTK available] |
| Modular System architecture: | Customized applications can be integrated by iMAR easily (please contact our sales for details). iNAT can provide arbitrary data and command protocols according to customer requirement, e.g. to substitute other navigation systems by iNAT (e.g. for Form-Fit-Function replacements) |
| EMI-EMC protection and qualification according to EN standards (railway), DO160G / MIL-STD-704D / MIL-STD-461E / MIL-STD-810G | |

### iRailLoc-C Series

iRailLoc-C, see figure 5, is a member of the advanced iNAT system family (iMAR Navigation and Timing) and is specially designed to the needs of modern train positioning, localisation and operation up to ATO (automatic train operation).

It provides the required PNTC features (positioning, navigation, timing & communication), all in one box, designed according to the relevant European railway standards regarding EMI/EMC, power supply and environmental impacts. The architecture of the iNAT systems allows also the aiding with any external position / velocity / time stamp / standard deviation data, e.g. obtained from machine vision, radar, LiDAR, magnetic sensing or any other application based aiding sensors (see figure 13).

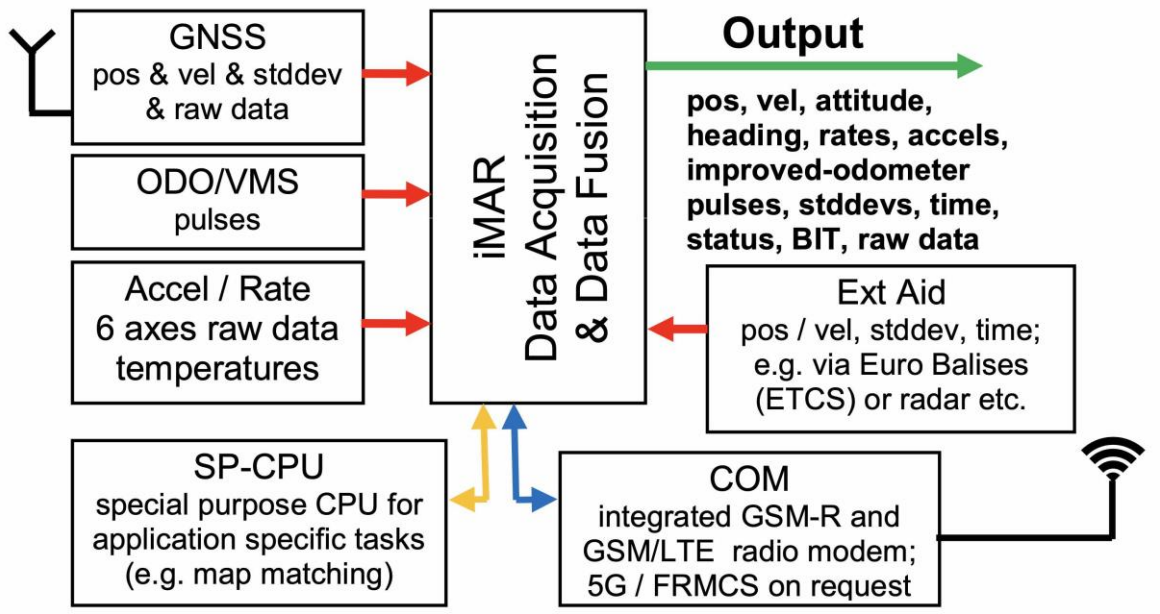



*Figure 13: iMAR's iRailLoc-C Series block diagram*

iRailLoc-C provides the relevant motion and position data for train location, train guidance and train control tasks and provides also open interfaces to auxiliary sensors on demand. All kinematic measurements like acceleration, angular rate, attitude, true heading, velocity and position of the rail vehicle are provided in real-time incl. timestamp and standard deviation with a data update rate of up to 500 Hz.

| | |
|---|---|
| Applications: | GNSS aided navigation, free inertial Navigation, attitude heading reference (AHRS) focused on railway applications |
| Real-time data output: | longitude, latitude, altitude / height, velocity, roll, pitch, yaw / heading, angular rates, acceleration, status, calibrated raw data INS/GNSS (for post-processing) |
| Interfaces: | 2 x isolated UART RS422 with common 24 V DC (max. 6 W) output<br>2 x isolated UART RS422 with additional PPS trigger output<br>2 x Ethernet 100 MBit/s (TCP/IP, UDP), NTP Time Server<br>up to 3 odometers supported (A or A/B opto-coupler; 3.5 ...30 V, 5 mA) with isolated supply output (15 V DC, 6 W max.), types of Knorr-Bremse, Baumer, Sick etc. supported<br>improved odometer output provided (A/B, RS422) to provide velocity with high accuracy (from data fusion, typically better 0.1 %) to ETCS-OBU to allow enlargement distances of ETCS balises (as option) |
| Radio Communication: | integrated GSM-R modem, integrated GSM/LTE modem with 3G/2G fall- back; 2 integrated SIM slots; optional one of both replaceable by integrated 5G modem; recommended antenna (GNSS multi-frequency, GSM-R, LTE): Huber & Suhner 1399.99.0152 (Sencity Rail rooftop MIMO Antenna) |
| EN 45545, EN 50121, EN 50155-2017 (certification in progress) | |

### iZET Series

The iZET series, see figure 8, is a small (232 x 202 x 111 mm), light (3 kg), energy self-sufficient GNSS and inertial localisation system intended for train integrity monitoring in automatic train operation (ATO) e.g. in ETCS L3 situations or any other operation requiring train integrity.

Methodically train integrity is determined by differencing vehicle speeds (train front and end side) [3] or redundantly through braking air pressure.

iZET may also be used for safe remote vehicle localisation and movement monitoring (without GNSS). iZET can quickly be mounted at any vehicle (including locomotives). Energy self sufficiency is realised with a battery buffered air pressure generator non-reactively connected to the train braking system. Braking system air pressure is permanently measured and reported through radio connection to e.g. central monitoring or to the locomotive.

| | |
|---|---|
| Applications: | GNSS and Inertial Navigation, attitude heading reference (AHRS), train integrity validation and air pressure monitoring on main brake pipe. |
| Real-time data output: | longitude, latitude, altitude / height, velocity, roll, heading, motion status, air pressure |
| Interfaces: | Aux. power output for ext. devices (e.g. camera or LiDAR): 24V/8W, Aux. 24V power input for maintenance purposes |
| | USB Host service, isolated UART RS422 with additional PPS trigger output |
| | Radio Communication to configure, incl. adequate antenna, Integrated GSM-R modem, integrated GSM/LTE modem with 3G/2G fallback, 2 integrated SIM slots, optional the modem is replaceable by integrated 5G modem. |
| EN 45545, EN 50121, EN 50155-2017 (certification in progress) | |

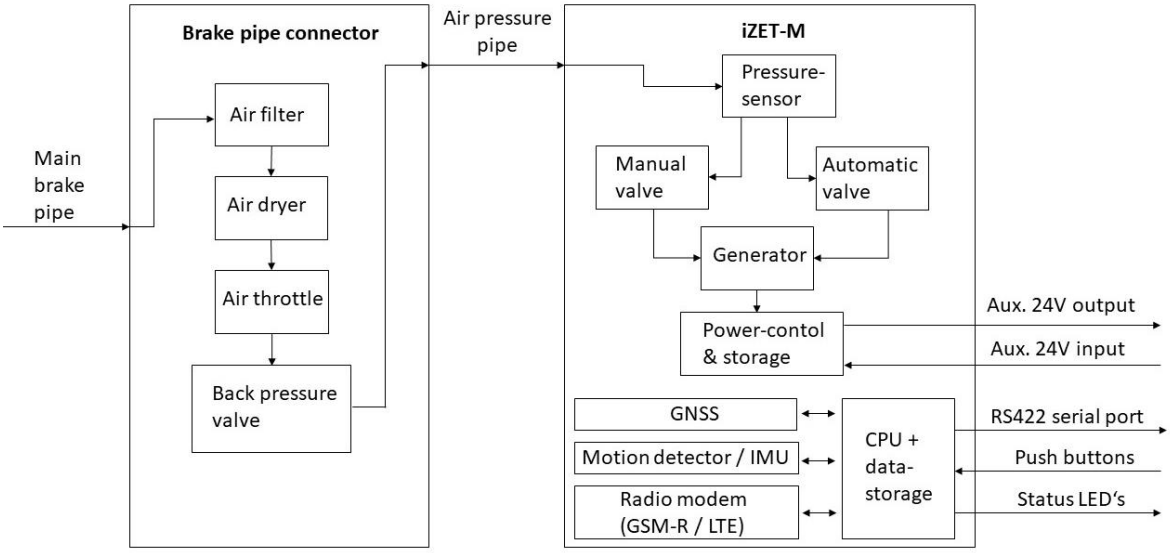



*Figure 14: iMAR's iZET series block diagram*

## iRAD Series

The iRAD series, see figure 4, is specially designed to meet a compact form factor enabling axle fitting within usual railway clearance profiles.

I combination with an integrated battery system an optional axle generator provides autarkic electric energy supply when used on cargo vehicles.

The iRAD Series is resistant to high g-shocks, more than 100 g due to the steel-on-steel wheel/track situation, and demanding railway environments. It provides highly precise attitude

[3] No GNSS or map is required making the system safe and easy to operate and maintain.

and localisation data for a variety of applications and uses cases including infrastructure (see figure 10) and vehicles condition monitoring (see figure 9) as well as train speed.

Apart from a separate special purpose CPU and external aiding input e.g. Euro-Balises or Radar iRAD provides similar functionalities as the iRailLoc-C series (see figure 14).

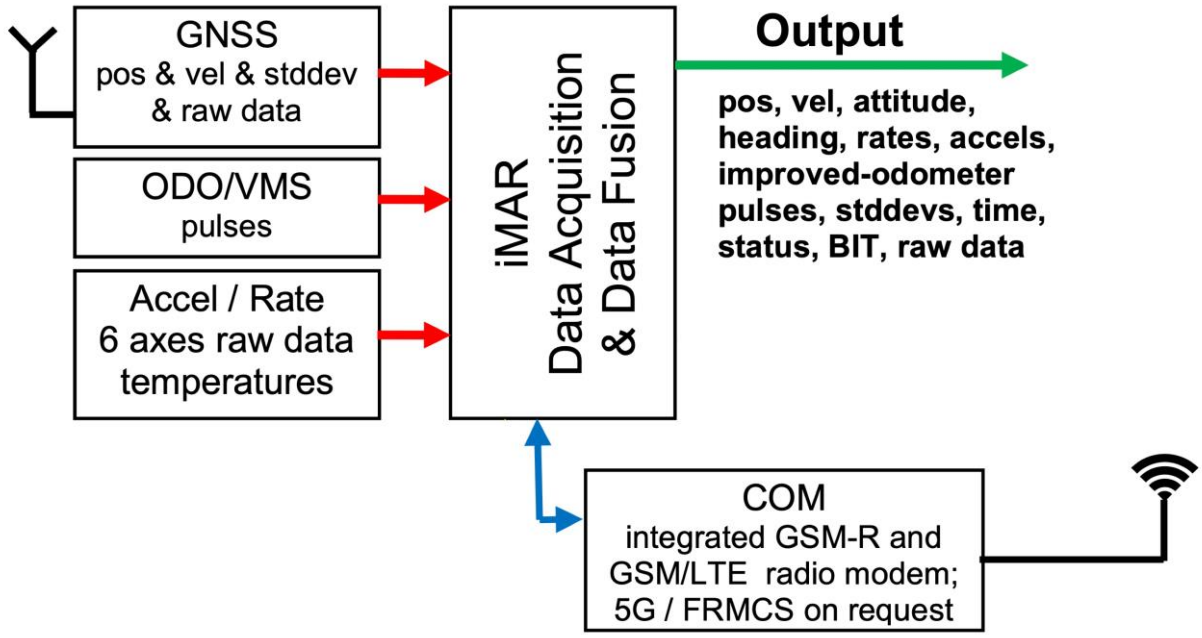



*Figure 14: iMAR's iRAD Series block diagram*