The on-board maritime PNT Module – Integrity monitoring aspects and first experimental results

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Abstract: The robust provision of position navigation and timing (PNT) information for vessel navigation is an objective of e-Navigation strategy identified by the International Maritime Organization (IMO). In this paper we will introduce the idea of a ship-side PNT Module as front-end between an integrated PNT system and ship-side applications like INS, AIS and ECDIS. The focus of this paper lies in the discussion of the integrity monitoring aspects of such a PNT Module. In the last part of the paper we will show first experimental results.

1. Introduction

The maritime integrated PNT System (Figure 1) is the sum of satellite-based, ashore and aboard components. The integrated use of these components enables the accurate and reliable provision of position, navigation and timing information to all maritime applications.

Position fixing systems are identified as one strategic key element of e-navigation [1]. Existing and future Global Navigation Satellite Systems (GNSS) like GPS, GLONASS and GALILEO are fundamental infrastructures for global positioning. Additionally, terrestrial services are used or considered as candidates to improve the positioning performance (augmentation services: e.g. IALA Beacon DGNSS, RTK) or to ensure the backup functionality (backup services: e.g. e-LORAN, R-Mode) respectively to GNSS. Due to their interoperability and compatibility these systems can be used alternatively or complementary for positioning, navigation and timing.

Several performance standards for shipborne GNSS and DGNSS receivers were developed and approved by IMO in the last decade: GPS, GLONASS, DGPS and DGLONASS, combined GPS/GLONASS, and GALILEO. A logical consequence of this standardization process could be the preparation of a new performance standard for a multi-system radio navigation receiver as core element of the on-board part of the PNT System (Fig.I). A more generally admitted approach can be achieved by the introduction of an onboard integrated PNT Module.

The on-board integrated PNT Module aims at the provision of position, navigation and timing information in accordance with changing performance requirements during berth to berth navigation. The core of the on-board integrated PNT Module is a value-added processing system (PNT Unit) using available radio navigation systems and services in combination with on-board sensors for accurate and reliable provision of PNT-information. The on-board PNT Module is on the one hand part of the integrated PNT system and on the other hand part of the on-board Integrated Navigation System (INS).

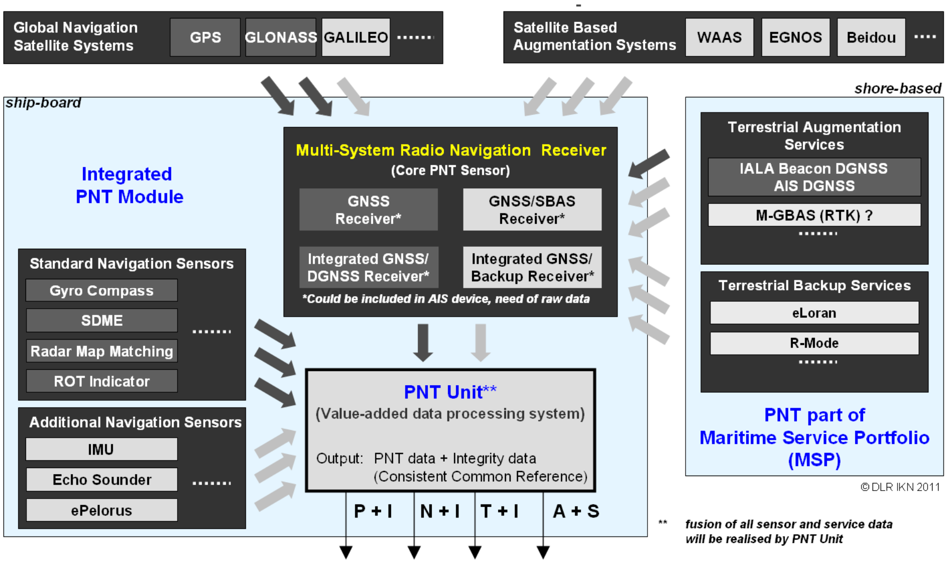

Figure I Integrated PNT System (dark grey: standard, light grey: considered options)

The idea behind the introduction of integrated PNT Module is, that from our prospective only the combined usage of all available navigation sensors will be able to satisfy the user needs such as “Indication and Improvement of Reliability” and “Alarm Management” [1] identified within the framework of the e-Navigation process. This integrated usage of navigation sensors improves the robustness of PNT information and enables the assessment of accuracy by suitable integrity monitoring functions. The type of implementable redundancy (equipment, different measurement methods, over determined systems, alternative applicable techniques) specifies the potential of error detection, identification and mitigation within the PNT Module.

2. Technical Requirements

One of the basic requirements to be clarified is the extent of PNT information delivered by a PNT Module. In a preliminary design, the following parameters are considered:

1. Position (longitude, latitude)
2. Under keel clearance (UKC)
3. Velocity: speed over ground (SOG) and course over ground (COG)
4. Attitude: roll, pitch yaw (heading)
5. Timing: UTC time

In the next step further additional requirements on the PNT Unit will be discussed.

In [1], the robustness of all e-navigation systems is requested. In order to fulfill this requirement, a definition of robustness needs to be given. We interpret robustness as the ability of a system to provide the output data according to their specification under changing application conditions and in cases of external disturbances (interferences, jamming, atmospheric influences). The robustness shall therefore be applicable to the realization of the basic functionality (output data with required accuracy) and integrity functionality.

In [1] it is furthermore stated, that requirements for redundancy, particularly in relation to position fixing systems, should be considered. Redundancy in a general meaning can be seen as the provision of an alternative system to support fundamental system functionalities. Within the Recommendation R-129 on GNSS Vulnerability and Mitigation Measures [3] IALA has given a classification of alternative navigation systems in relation to their aims:

1. A **redundant** system provides the same functionality as the primary system, allowing a seamless transition with no change in procedures.
2. A **backup** system ensures continuation of the navigation application, but not necessarily with the full functionality of the primary system and may necessitate some change in procedures by the user.
3. A **contingency** system allows safe completion of a manoeuvre, but may not be adequate for long-term use

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For the introduction of additional sensors to the integrated PNT Unit, this classification scheme needs to be considered.

3. Sensors for an onboard PNT Module

In a scalable design different sensors could be used in an onboard PNT Module. These sensors can be distinguished into exiting maritime standard sensors and possible additional sensors. An overview of the sensors and a discussion of the related standards can be found in [4]. Here only a list of sensors and their output parameters should be given. The rows with white background represent the standard sensors, whereas the rows with dark background represent the non-standard sensors which will be shortly introduced in the latter parts.

TABLE I. SENSORS AND OUTPUT

	Pos	COG	SOG	True Heading	ROT	Time	UKC
Major GNSS device	M	M	R			M	
Second GNSS device	R	R	R	R	B	R	
Second GNSS system	R	R	R			R	
Second GNSS signal	R	R	R			R	
EM Log			B				
Doppler Log			M				
Magnet Compass				B	B		
Gyrocompass				M	B		
THD					B		
ROT indicator					M		
Echo sounder							M
IMU	C	C	C	C	C		
e-Loran	B					B	
R-mode	B					B	
e-Pelorus	C			C			

R: Redundant B: Backup C: Contingency M: Main sensor

Due to vulnerability of GNSS adequate backup or contingency systems are required in the GNSS system failure event. Using the standard sensors it is difficult to handle GNSS outages, and hence the following techniques can be considered:

(A) Carriage of an additional GNSS device

Once the major GNSS device (antenna or receiver) is out of use, the second GNSS device can fully take the function of the major GNSS device. However, the redundant GNSS device is also affected by propagation errors of radio signal (without multipath). In this sense, the significance of a redundant GNSS device is reflected during the internal failure of the major GNSS device.

(B) Use of two ore more frequency receiver for future GNSS

The upcoming availability of additional civilian code on frequencies besides the L1 band signals will offer new opportunities. Due to different carrier signals, the other carrier signals might not suffer from the same interference or jamming as the L1 signal. Also, the channel failure (loss of lock or cycle-slips, etc.) for L1 signal might not occur simultaneously on the other frequencies. Hardware failure of receiver or antenna might also challenge the reception of all carrier signals.

(C) Multiple GNSS systems

Two or more full-operational GNSS could serve as redundancy for each other, as they realize same functions in maritime navigation as specified in [6]. Once one GNSS system is shut down or temporarily out of service, its function can be replaced by another full-operational GNSS system.

(D) Terrestrial navigation system

Such systems like e-Loran or R-mode facilitate the functions for positioning and time determination, so that these systems could serve as backup for GNSS.

- *e-Loran*

e-Loran, the modernized version of Loran-C, is a long-range radio navigation system, operating at an assigned frequency of 100 kHz. Currently there exists a pre-operational e-Loran network in the UK and Ireland. Although the United States switched off their Loran-C service, operational Loran-C services can be found in parts of Russia and Asia. So the future of e-Loran as a terrestrial backup for GNSS with a large coverage area is currently under discussion. Also, the fulfillment of the future maritime requirements in the accuracy is an issue.

- *R-Mode*

In [2], the Ranging-mode (R-mode) is seen as a possible novel variant of positioning technique using terrestrial signals. The idea is to use existing communication channels and append their functionality by sending an additional timing signal. From the time difference between signal transmission and reception, the ship should be able to determine its position. The advantage of this idea would be, that at least partially existing infrastructure could be used. Currently this is still only an idea and the concept needs to proven.

(E) Inertial Navigation (IMU)

The development in the field of inertial sensors, with increasing quality of rather low cost sensors, makes inertial navigation attractive for future civil maritime applications. Inertial navigation can bridge GNSS outage within certain duration and can therefore be seen as a short-term contingency for the navigation. Additionally it enables integrity monitoring for position and navigation information.

(F) e-Pelorus

The positioning relies on the bearing angles obtained from optic sensor with respect to known terrestrial objects. More than two bearing angles allow the horizontal positioning. The use of such a technique needs the objects with known coordinates and simultaneous tracking of several objects. For this purpose, an 'electronic pelorus' is proposed [2].

4 Proposed architecture of integrity monitoring in a PNT Module

The core element of the proposed PNT Module is the PNT Unit as a value added data processing system. By using sensor and data fusion methods the PNT Unit is responsible for generating the basic PNT information together with integrity information for the data. The integrity monitoring can be carried out in three sequential steps. The first step is an individual sensor data test. The second step is the compatibility test of similar data from different sensors. The third step is the fault detection and identification in the integration algorithm. A general integrity monitoring approach is depicted in Figure II.

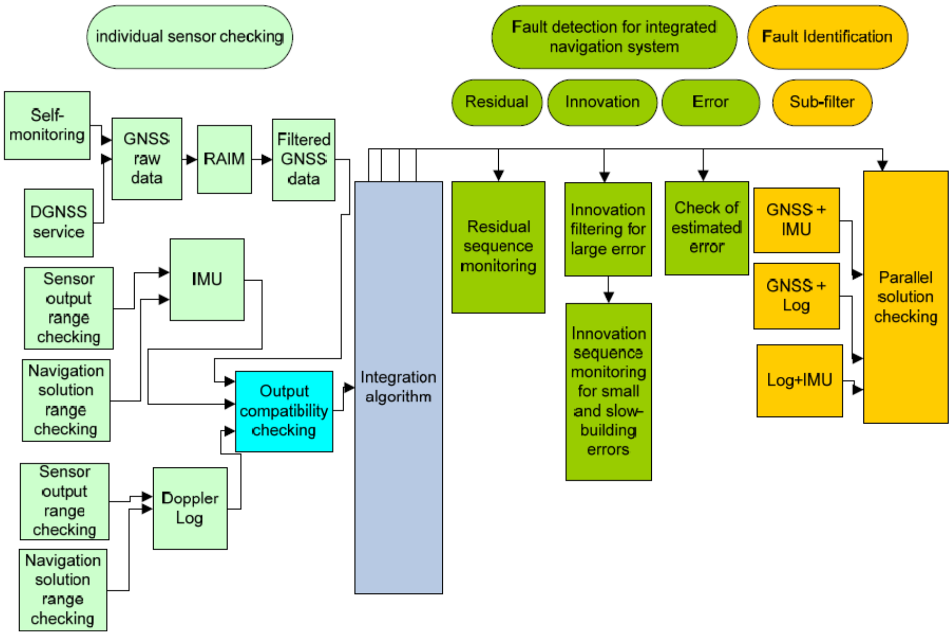

Figure II General integrity monitoring approaches in the integrated sensor system

4.1 Integrity monitoring in integration algorithm

The plausibility tests, validity tests and compatibility tests are suitable for detecting gross sensor failure but not sensitive for slight error, time-variant errors and drifts. The Kalman filter-based algorithm could offer high sensitivity of detecting these errors. Integrity monitoring based on Kalman filter can be categorized into the following approaches [5].

- *Kalman filter estimates (bias check)*

In a Kalman filter, the errors of navigation parameters can be estimated. If an estimated error is significantly larger than the error level specified by the manufacturer, it is likely to be a failure in the sensor.

- *Innovation-based approaches*

The innovations indicate the consistency of the actual measurements and the measurements predicated by state estimates. Innovation filtering may be used to detect large discrepancies immediately, whereas innovation sequence monitoring enables smaller discrepancies to be detected over time.

- *Residual-based approaches*

The above-mentioned innovation filtering and sequence monitoring can also be expanded to residuals. Residuals have a smaller covariance than innovation, making them more sensitive for error detection [5]. The only shortcoming is that the processing of residuals is not an essential part of a Kalman filter routine and needs extra computing time.

- *Parallel solution of multiple sub-filters*

Parallel-solutions integrity monitoring maintains a number of parallel navigation solutions or sub-filters, each excluding data from one sensor or radio navigation signal. Each additional navigation solution is compared with the main filter using a consistency test. A significant inconsistency indicates a fault in the sensor or signal omitted from main filter. The system output is then switched to the solution omitting the faulty sensor or signal. The main drawback lies in the increased computational burden and hence this technique is preferably used for failure identification rather than failure detection

5. First experimental results

In order to collect test data for the development and test of the software routines for the PNT Unit, first measurement campaigns have been performed in cooperation with the Federal Maritime and Hydrographic Agency (BSH) on the survey and research vessel DENEB. For these experiments the vessel was additionally equipped with 3 GNSS antennas and receivers (type: Javad Delta) and an IMU (type iMar IVRU FCAI). In Figure III the vessel “DENEB” is shown, where the red circles mark the positions of the 3 GNSS antennas and the yellow circle indicates the position of the IMU installed near the centerline inside the vessel.

Figure III survey and research vessel DENEB

In this paper first data analysis of a measurement campaign performed on July 5th in the port of Rostock is presented. In Fig. IV (a) the trajectory of the vessel is shown. Coming from the Warnow River the vessel performed an anti clock wise turning maneuver on the turning circle and finally it left the port and led into the Baltic Sea.

As mentioned in the last section, the second step in the integrity monitoring approach is the compatibility check for PNT data derived from different sensors. As one example in Fig. IV (b) the rate of turn (ROT) measured by the IMU and ROT derived from heading data of the Gyro Compass is shown. Within the specific time interval, no significant systematic differences between both curves can be found. In contrary to that, the ship speed measured by the Doppler Log, Electromagnetic (EM) Log and the GNSS receiver (1) shows systematic differences (see Fig. IV (c)). The biggest differences can be observed within the time interval of the turning maneuver. One reason could lay in the fact, that the EM Log measures the speed through water (STW) while GNSS and Doppler Log measure speed over ground (SOG). Another reason could be the different

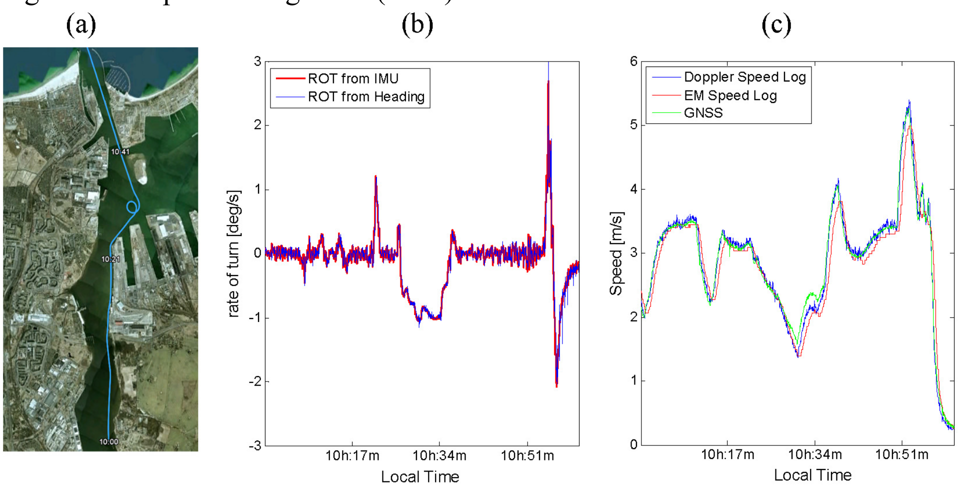

Figure IV (a) trajectory of vessel DENEB (on Google maps),
(b) the ROT derived from Heading and read from IMU
(c) Speed obtained from different sensors

positions of these sensors on the ship. In order to check this, the SOG measured by the three different GNSS receivers is plotted in Fig. V. Here the measurement principles and algorithms are identical and hence the only difference is the position of the antennas on the ship (see. Fig. III).

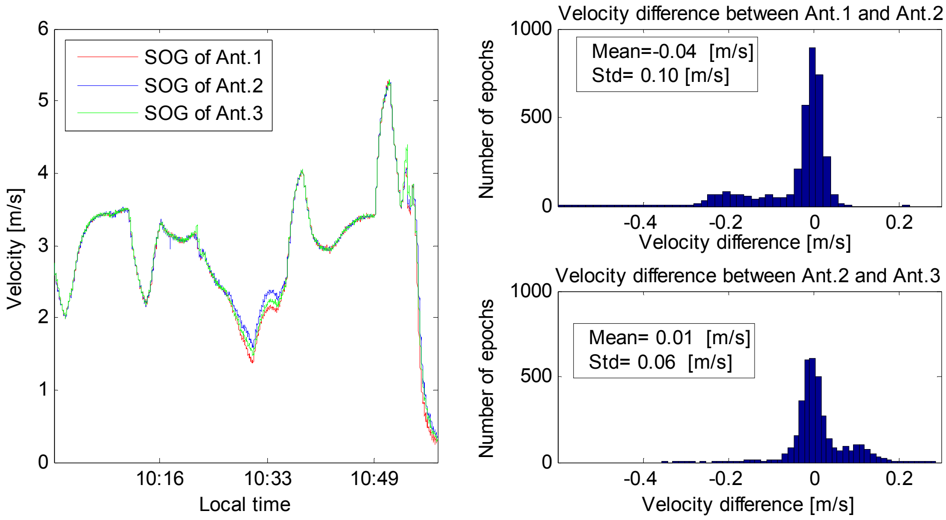

Figure V SOG and SOG differences determined by the different GNSS antennas and receivers

Fig. V shows that significant deviations of SOG-information obtained from different GNSS receivers occur during the turning maneuver. The largest differences can be found between the fore antenna (1) and the aft antennas (2+3). This clearly indicates that the observed differences are caused by the different sensor locations on the vessel body. These results yield to the following consequences for a compatibility check of the SOG data from different sensors:

a) For a compatibility check with the SOG information obtained from different sensors larger differences need to be accepted (at least during special maneuvers) or

b) The SOG measured by the sensors would need to be transformed into a consistent common reference point by using additional information of the actual vessel attitude and angular rates.

Option (b) has the disadvantage that the integrity tests for one output parameter (here SOG) depends on the availability and integrity of another output parameter (here attitude and angular rates).

5. Summary

This paper focuses on a maritime integrated PNT Module as the on-board part of maritime PNT system. The aim of the PNT Module is the robust provision of position, navigation and timing information in accordance with the performance requirements of the actual operational region. The core of the PNT Module is a PNT Unit. This PNT Unit is a processing system, which combines by means of sensor and data fusion methods all available PNT sensors. The PNT Module is on the one hand part of the integrated PNT System and on the other hand part of the on- board INS. After a short discussion of the sensors of a PNT Module we have introduced a preliminary integrity monitoring concept for a PNT Module. In a first step towards the development of a PNT Module demonstrator system we have performed first measurement campaigns and derived PNT output data from different sensors. The analysis of these data shows, that for their usage within compatibility tests, the different locations of the sensors onboard the vessel needs to be considered.

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