PNT-data generation as basis for guidance systems in inland water traffic

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Abstract

The use of Global Navigation Satellite Systems (GNSS) in maritime applications has been widely recognized as an essential part of maritime navigation. This is due to good reception conditions on open water and due to the low accuracy requirements when navigating on the open sea. When it comes to inland waterways, GNSS is an important tool for the measurement of navigational data and position. In this context, a reliable navigational solution is the base for the implementation of applications for advanced assistance during berthing or bridge and lock passing. However, exactly these applications pose a challenge to a GNSS-based positioning solution, since the critical navigation-areas are often also those with restricted reception conditions. To ensure continuously accurate position navigation and timing (PNT) data, a so called PNT-Unit has been designed based on the fusion of GNSS, inertial (Inertial Measurement Unit - IMU) and other ship-borne sensors. One of the goals of the project PiLoNav (Precise and Integer Localization and Navigation in Rail and Inland Water Traffic) is the development of a manoeuvre guidance system tailored for these critical scenarios. Since the driver assistance will be based on absolute positioning, a precise survey of the environment is required as well as the precise vessel position and navigation states. While the first is a question of the quality of the underlying map the determination of latter parameters proves difficult.

1. Introduction

Transport capabilities are a key precondition to an efficient and smoothly running economic system. In the European economic area the inland traffic carriers are road, rail and inland waterways. Several studies that examine the cost per ton-mile ratio of these carriers arrive at the conclusion that inland waterways are the most efficient means of freight transport [1]. This assessment is made for direct transport costs as well as external costs such as noise and air pollution [2].

Inland waterways as a sustainable and competitive means of transport have been recognized by the European Commission through the programme NAIADES as well as by the German Government in the context of the national "Nachhaltigkeitsstrategie" (Sustainability Strategy), aiming to increase the percentage of goods transported via inland waterways to 14% until 2015. With the consequent increase in traffic, new and advanced traffic management systems and technologies will be necessary, to aid maintain smooth, safe and efficient passage along the waterways. Basis of these systems is the knowledge of navigational parameters such as position, heading, and speed over ground of the own vessel as well as other relevant traffic along the waterways.

The utility of Global Navigation Satellite Systems (GNSS) in maritime applications has been widely recognized over the last decades to deliver navigational parameters, and is today an essential part of almost any maritime navigational or tracking solution. This is on one hand due to favourable reception conditions on open water, and on the other hand to the relatively low accuracy requirements to navigation on the open sea. Also in inland waterways, GNSS has been accepted as an important tool for the measurement of navigational data and position, but in critical situations navigation by sight as well as radar-imaging are considered as the standard approaches. While radar is a powerful aid to a skilled ship's master, the automated analysis of the data for advanced driver assistance applications proves difficult. In this context, a reliable GNSS-based navigational solution is a necessary basis for the implementation of safety-critical applications such as automatic manoeuvre guidance or other advanced assistance systems for critical manoeuvres such as berthing, bridge and lock passing.

However, exactly these applications pose a challenge to a GNSS-based positioning solution, since the areas, that are critical to navigation, are in many cases also those with restricted reception conditions [3].

The remainder of this paper is structured as follows. Section 2 introduces to the project PiloNav. Where Section 3 explains the investigated navigation data, Section 4 presents results based on real measurement data collected on an extended measurement campaign. Section 5 concludes the paper and gives an outlook about future tasks.

2. Project PiloNav

2.1. Introduction to PiloNav

The goal of the Federal Ministry of Economics and Technology (BMWi) funded project PiloNav is the development of a generic location platform which can be used on different transport carrier to determine highly accurate and integer position, navigation and timing data (PNT) with the focus on rail and inland-water traffic. Therefore, carrier-specific sensors (IMU, radar, optical sensors, etc.) will be merged with position, navigation and timing information obtained by GNSS and therefore to form an integrated navigation system. In case of inland-water traffic this is referred to as a Positioning, Navigation and Timing-Unit (PNT-Unit) [17] and in case of rail traffic as a Train Location Unit (TLU) respectively.

On the application layer this PNT data will be used as input for driver assistance and manoeuvre guidance systems which continuously provides reliable information and assists the driver with critical manoeuvres in order to optimise rail and inland-water traffic and to meet the requirements in terms of efficiency and environmental challenges [4, 5]. This work, however, focuses on the inland water aspect, where the inland water transport-relevant goals of the project can be formulated as:

- the development of an inland water PNT-Unit,
- the development of a manoeuvre guidance system to enable a time- and resource efficient passing of bridges, locking of vessels, and to plan and to perform evasion manoeuvres in case of oncoming traffic,
- and the validation of the integrated manoeuvre guidance system with simulated data and by experimentation.

The next paragraph shortly describes the components of the PNT-Unit as data source.

2.2. The PiloNav PNT-Unit

In order to evaluate the determined PNT-data, accuracy and integrity requirements have to be formulated [18]. Requirements on navigational parameters are defined within the "e-Navigation Initiative" by the International Maritime Organization for seaborne navigational systems and services, where inland water is defined as sections between the open sea and the harbour [11, 12, 13]. However, in this work denotes inland water application as vessel navigation on rivers. First requirements on navigational parameters are defined by IRIS projects [16]. Critical manoeuvring procedures (locking, automated docking, bridge passing, etc.) demand highest requirements on the PNT data generation. To avoid collisions with lock gates, or bridges cm-accuracies have to be achieved. Moreover, considering the opportunity of trajectory optimisation, the project PiloNav formulated extended requirements on navigational parameters for aimed project developments which are significantly higher than maritime requirements formulated by the IMO [14, 15]. A detailed comparison can be found in [3].

Due to the good availability of global navigation satellite systems, GNSS became a widely used technique for positioning and navigation on inland water vessels. Consequently, two GNSS sensors are used as main sensor for the generic location platform. Compared to open sea, inland water vessel navigation has the advantage that ground-based reference services can be used to improve the positioning by satellite based sensors. Therefore, Real-Time Kinematics (RTK) will be used to complete the satellite-based part of sensors. Measurement campaigns show that the application of GNSS-based sensors and additional GNSS-based services only does not suffice the demanded requirements due to environmental or infrastructural conditions [4]. Moreover, additional sensors have to be integrated. In particular, an Inertial Measurement Unit (IMU) will be used to compensate loss of satellite signals and multipath effects. This concludes the generic platform for both, rail and inland water traffic. As inland water vessels have less mandatory equipment than their maritime counterparts additional sensors and services have been identified within PiloNav in order to fulfil the requirements formulated in [3]. In particular the choice of sensors covers three GNSS sensors to derive all navigational states including integrity information. This is also one of the main advantages of the PNT-Unit approach - the capability of improved integrity monitoring by using sensor fusion techniques. In order to provide this information, the definition of performance requirements (accuracy regarding position, velocity, attitude) is needed. For instance the horizontal positional accuracy is of high importance for berthing manoeuvers as for bridge passing, where the vertical accuracy is crucial. This means, the quality of the output parameter should be evaluated by accuracy, integrity, continuity and availability for different operational areas (e.g. regular waterway, bridges, lock/port).

2.3. Inland Water Manoeuvre Guidance

Knowing the position and navigational states of a vessel only is not sufficient to design and conduct sensible vessel movements. Uncertainties which have an impact on the traffic flow have to be detected and analysed. These uncertainties one distinguishes between static (bridges, locks, quay walls) and dynamic (position and navigational states of other vessels) factors. Both have to be analysed to be able to predict the development of the traffic situation and respond in a timely manner. Where digital maps, such as Electronic Navigational Charts (ENC), can be used to recognise the occurrence of static factors affecting the calculation of optimal trajectories or evasive manoeuvres, dynamic factors have to be monitored using ship-borne or so-called application sensors such as radar and the communication system AIS (Automated Identification System). Figure 1 right displays the architecture of the manoeuvre guidance system for inland water vessels. The subject of this work is the computation of the elements for the trajectory optimisation which is part of the manoeuvre planning module (green box in Figure 1 right). For a detailed description of the remaining modules (Sensor & Data sources, Data Preprocessing and Data Processing) the reader is referred to Vierhaus et al in [4]).

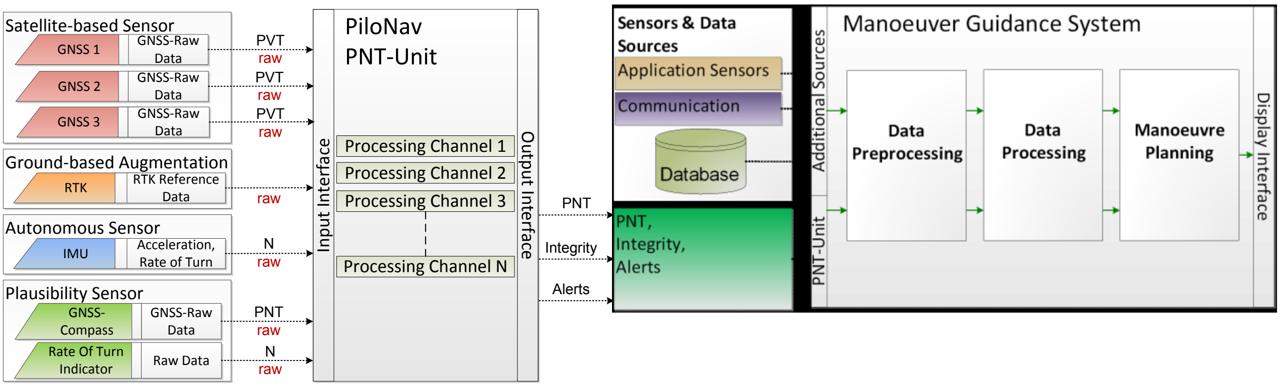


Figure 1: Concepts of (a) PNT-Unit and (b) Manoeuvre Guidance System

The Preprocessing module is used to calculate the adapted manoeuvre space taking the traffic situation (Tactical Traffic Image - TTI) and the geometry of the own vessel into account. The Processing module then is determining distances to static and dynamics obstacles and generating short-term collision warnings if the distance violates a defined threshold. Following, mathematical optimisation functions can be used for an optimised manoeuvre planning [6]. Based on the PNT-data and TTI the manoeuvre guidance system provides the elements of the optimal trajectory consisting of velocities and heading information as well as strategic navigational tasks such as encounters with other ships as well as tactical tasks like bridge and lock passing. The goal of this system is, in the first step, to compute a plan for an optimal manoeuvre for the next route section. The planned manoeuvres will be optimised in terms of the criteria safety as well as time- and resource-efficiency.

3. Demonstration Area and Data Basis

3.1. The PiloNav test bed

To test and demonstrate the performance of the PNT-Unit as well as the driver assistance system a test bed was selected which enables various typical ship manoeuvres such as berthing, bridge and lock passing. The selected test area is located on the river Moselle close to the lock of Koblenz (see Figure 2). The test bed has a range of about 3 km and stretches from the entrance of the river Moselle into the river Rhine (Moselle km 0.0) until the headwater of the lock Koblenz in the western direction (Moselle km 3.0).

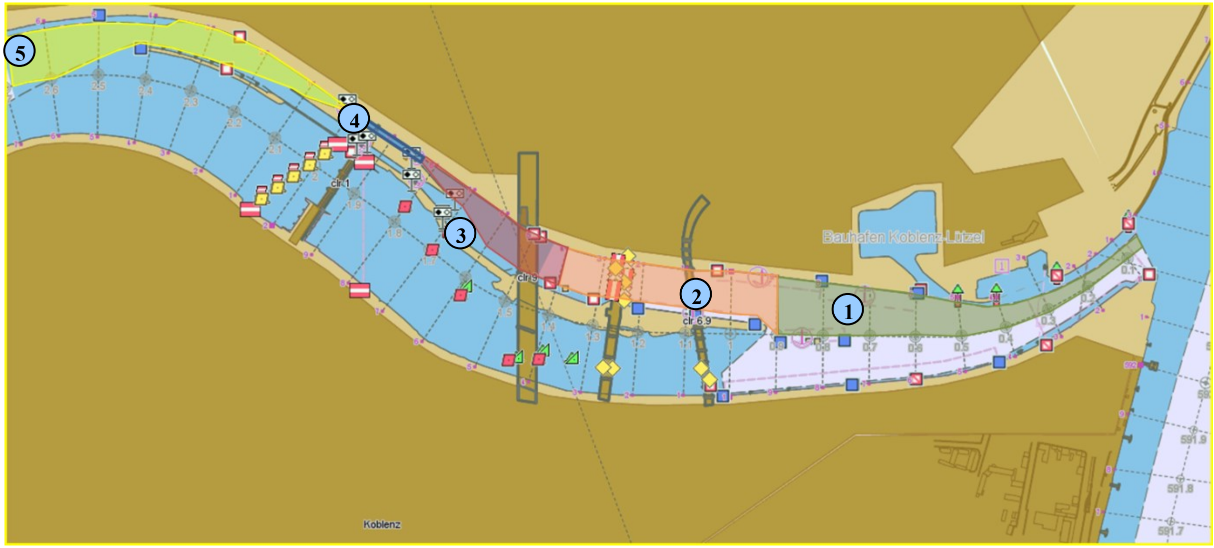


Figure 2: Overview of the PiloNav demonstration area

As illustrated in Figure 2 the PiLoNav test bed is subdivided in five sectors with different requirements for the PNT-Unit concerning to accuracy, integrity, continuity and availability. Furthermore the sectors have different conditions concerning the reception quality of GNSS signals, mainly caused from bridges and piling walls. Table 1 provides a coarse overview about the different sectors and the resulting PNT requirements as well as the specific ambience conditions.

As shown in the Table 1 sectors 1 and 5 are areas which have standard requirements for the PNT. The GNSS reception in these areas is expected to be typical for an urban environment, with only marginal effects concerning multipath and shadowing. In contrast to this the sectors 2, 3 and 4 enable a very challenging test of the PNT-Unit and the driver assistance system. Especially in sector two the passage through the railway bridge is requiring a very precise positioning and attitude determination from the PNT-Unit in the horizontal and vertical domain. The passing of the arches with a width of 14 m and a height of 5.23 m (based on the highest shipping water level) enables the evaluation of the manoeuvre guidance and the bridge height warning function within the PNT-Unit. Another challenge in this area is the limited use of GNSS which needs to be compensated with the integrated IMU. Sector three requires also the provision of very accurate PNT data to enable the manoeuvre guidance for the entrance into the lock. Like Sector two this area is also affected by partly bad GNSS reception. Sector four has the highest demands on position accuracy because of the lock width of only 12 m. Comparing the lock dimensions with the typical size of inland vessels (length: 170 m, width: 11.60 m) results in a remaining space between ship and lock of only 20 cm. Again, the GNSS reception in this sector is also difficult because of the nearby piling walls and the entrance of the lock chamber in the tailwater.

Table 1: Description of test bed sectors

Sector	Moselle km	Description	PNT requirements	Ambience conditions
1	0 - 0,9	Entrance into the Moselle river	Standard PNT requirements (2D)	Normal GNSS reception
2	0,9 - 1,4	Bridge passage (railway bridge with arches);	High PNT requirements (3D)	Significant shadowing of GNSS caused by metallic walls and two bridges
3	1,4 - 1,85	Lock entrance	High PNT requirements (2D)	Significant shadowing of GNSS caused by metallic walls and one bridge
4	1,85 - 2,0	Lock chamber	High PNT requirements (2D)	Significant shadowing of GNSS caused by lock chamber
5	2,0 - 3,0	Lock exit to headwater	Standard PNT requirements (2D)	Normal GNSS reception

To enable the position determination with accuracy in the range of 10 cm, a RTK station is installed at the lock of Koblenz to broadcast GNSS phase corrections in the test bed. In addition the test bed is also within the broadcast area of a nearby AIS base station. This facilitates the use of water level information based on permanent gauge measurements. The use of up to date water level measurements enable an independent calculation of the clearance between the highest point of the vessel and the bottom line of the bridge.

3.2. Set guiding lines and waypoints in the demonstration area sectors (ideal line)

One basic objective of the driver assistance system is that the vessel should follow a given guiding line from a starting point (Moselle km 0.0) to a target point (Moselle km 3.0). The guiding line consists of different waypoints. Every point describes a point where the vessel has to change the course. For the definition of an ideal line the fairway depths and widths, navigation rules, anchorage area and bridge crossings have to be taken into account. To determinate an ideal line for the use within the PiloNav demonstration area an analysis of traffic lanes based on AIS recordings were carried out. The main goal was to obtain typical routes of inland vessels in the test bed area for up- and downstream passages. An example of the traffic analysis is shown in Figure 3 for upstream going vessels.

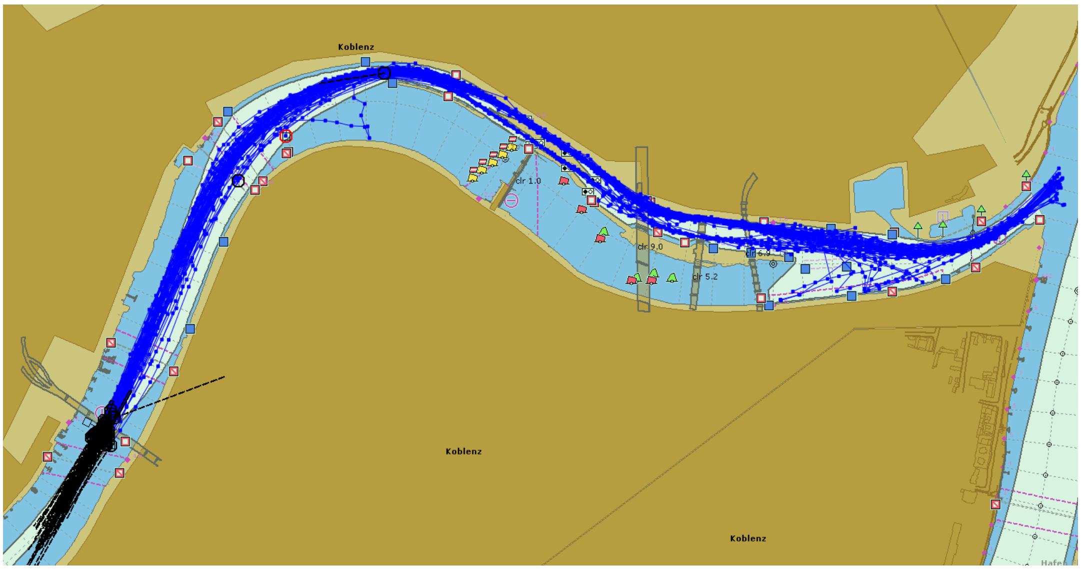


Figure 3: Analysis of AIS recordings for upstream vessels in the PiloNav demonstration area

As shown in Figure 3 the inland vessels going upstream are using different routes depending on the lock chamber they will use and the traffic situation existing in the tailwater area of the lock. As a result from the analysis of the complete AIS recordings three static “ideal” routes were determined, two for upstream traffic (to reflect the two major approaches to the lock) and one for shipping downstream. The routes and waypoints are provided as digital data base which is used for the manoeuvre guidance processing within the PNT-Unit.

3.3. Data Acquisition

The demonstration area at the river Mosel in Koblenz is characterized by three bridges and a lock, with a railway bridge as the most challenging infrastructure (Figure 4). Therefore their position and shape have to be measured with a high accuracy.

The local reference system (ETRS89) has been defined by four points, determined by static GPS measurements at the lock (Figure 5). The following site measurement of the lock has been done with a horizontal accuracy of 2.5 cm.

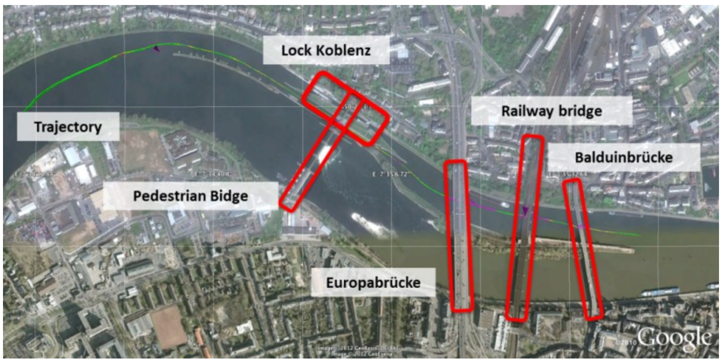


Figure 4: Demonstration Area and Trajectory

Figure 5: Locking chamber with 4 GPS-reference points which realized the reference system

For the collision avoidance system it is crucial to determine clearance of the rail bridge with a cm-perfect vertical accuracy. As the bridge is hardly accessible, a tachymeter in reflector-less mode has been used (Figure 6, left), which causes additional errors. A vertical accuracy between 3-10 cm has been achieved.

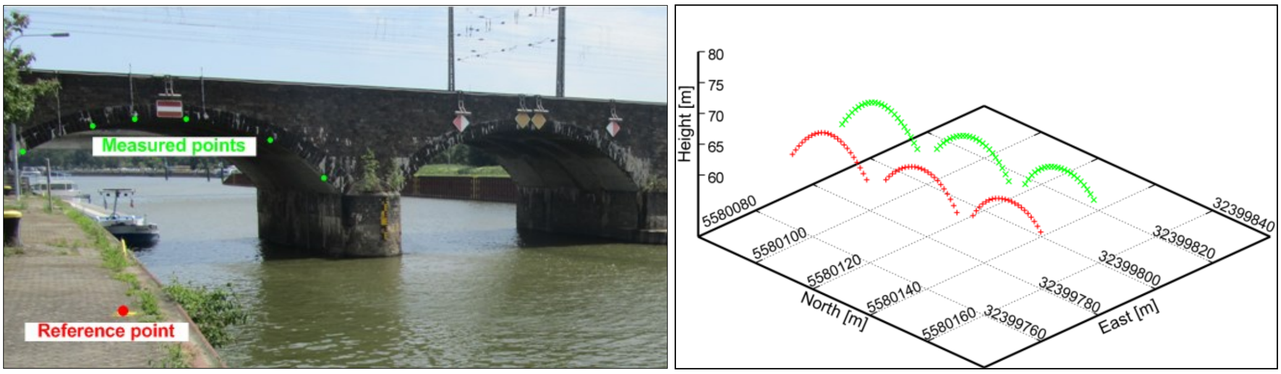


Figure 6: Arches of the bridge with measured points (left) and the modeled arches on both sides with polynomial 4th degree (right)

Additionally the positions of the sensors on-board the demonstration vessel (GNSS, IMU, application sensors, Figure 7) and the shape of the vessel itself have to be determined. This measurement was realised with a horizontal and vertical accuracy of about 1-2 cm.

Figure 7: Vessel BS Mainz with all sensors elements

3.4. The Measurement campaign

In order to collect test data for the development and test of the PNT-Unit, measurement campaigns have been performed in cooperation with the German Federal Waterways and Shipping Administration for Navigation Techniques (FVT) on the vessel MAINZ in August 2012. The vessel was equipped with three GNSS antennas and receivers (Javad Sigma), an IMU (iMar IVRU FCAI) and a commercial GPS Compass (JRC JLR-20).

During three passes of the Koblenz lock and the bridges (see Figure 4), six hours of dynamic data have been collected. In order to stress the heading determination and to investigate the influence of the inertial measurement unit in more detail, some special manoeuvers have been sailed. That is, on Rhine river an 8-shaped trajectory and various turns. Moreover, a part of the trajectory will be investigated, where bridges block the GNSS signals and the IMU has to stabilise the position estimation and therefore the heading determination.

3.5. Simulation environment

The evaluation of the performance of the developed algorithms implemented in the PNT-Unit is often a challenge, making the usage of simulated data for the test of these algorithms a feasible and commonly used approach. Due to its nature, the factors that influence RF-signals cannot be simulated comprehensively. This drawback could be solved by conducting extensive measurement campaigns. However, they are usually very expensive in time and financial matters and their results for the case of the PNT-Unit cannot be reproduced due to the changing environment (e.g. water level, satellite constellation, ionospheric and tropospheric changes). Therefore a record and playback system has been used to record the extensive High-Frequency (HF) data as it arrives at the GNSS antenna, naturally including all error sources occurring during the measurement such as multipath effects and signal interference.

Table 2 depicts a conceivable configuration for the Record- and Playback-Unit using three GPS receivers and antennas, reference data for a differential augmentation system, an AIS antenna, an IMU and a laser distance meter.

Table 2: Possible sensor data for record and playback

Sensor	**Data**	**System**
GNSS 1	RF GPS L1	RF Recorder/Player
GNSS 2	RF GPS L2	RF Recorder/Player
GNSS 3	RF GPS L1	RF Recorder/Player
Automatic Identification System (AIS)	RF AIS/ NMEA AIS	RF & LF Recorder/Player
Real Time Kinematic (RTK)	RF RTK/ RTCM RTK	RF & LF Recorder/Player
IMU	Lateral Accelerations, Rotation Velocity	LF Recorder/Player
Laser scanner	Distance	LF Recorder/Player

4. Analysis

4.1. PNT Data Generation

The algorithms for PNT-Data generation are realised in an existing C++ framework [20]. Various algorithms are used to create software processors as depicted in Figure 8 and are connected in parallel and/or serial mode to achieve the desired results. The sensor data for the calculations was recorded during the measurement campaign into a SQLite database like described in chapter 3.4. As a result the data can be used repeatedly which is crucial for the fine tuning of the algorithms.

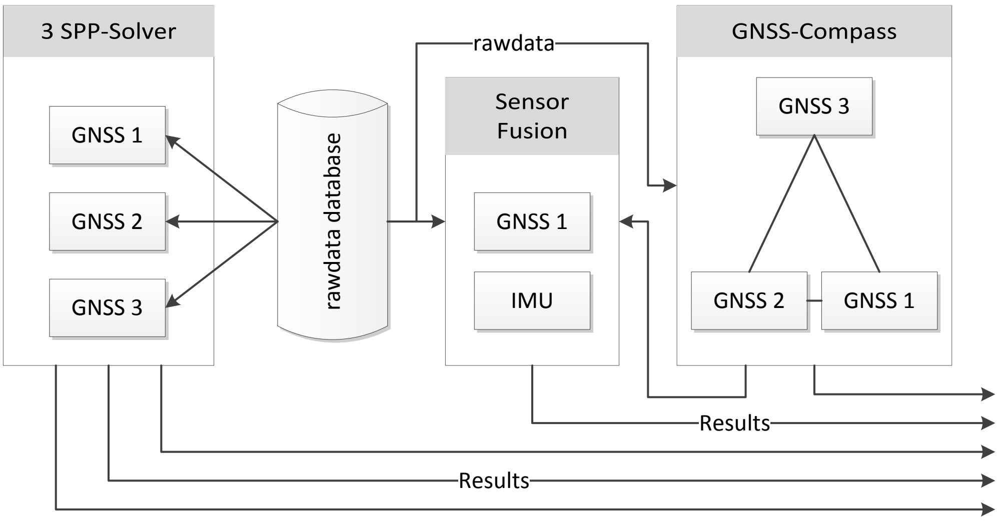


Figure 8: Overview of the main parts of the PNT-Unit.

Some of the aforementioned processing chains were used to create the results, this paper focuses on. One of the central processing chains is the sensor fusion. Here GNSS and IMU observations are fused in a tightly coupled approach, meaning that the pseudorange and Doppler observations of the initially defined GNSS receiver are used in the Extended Kalman Filter (EKF). If the selected receiver is not providing data for any reason, another one is selected and the EKF is restarted. The EKF is based on 17 states (positions: X, Y, Z; velocities: v_x, v_y, v_z; accelerations a_x, a_y, a_z; attitude parameters: roll, pitch, yaw with their according turning rates; receiver clock bias and receiver clock drift) and uses information from the attitude providing sensors aside from the GNSS observations. This means that the classical measurement vector (containing pseudorange and Doppler observations) is extended by introducing roll pitch and yaw from a GNSS compass additionally. If the ship has a gyrocompass installed, the yaw derived from it can be added as well.

To ensure reliable results several tests are carried out to only use observations that can be trusted on a very high level. To achieve this, the three single point processors (SPP-Solver

in Figure 8) are outfitted with a code based snapshot RAIM (Receiver Autonomous Integrity Monitoring), applying weights to the observations of each satellite according to the trust that can be put in it. Consecutive measurements are checked if an unreasonably large step occurred and also excluded according to the satellite health-status message.
The following chapter focuses on the analysis of the ships heading.

4.2. Heading determination

The heading determination refers to a specific body coordinate system [19]. For example, the heading obtained from a GNSS compass reflects the deviation angle between a specific antenna setup and the true north, whereas the IMU heading is based on the X-axis of the IMU body frame. In the following discussions, the heading reflects the deviation between the ships longitudinal axis and the true north direction.
The heading of the ship can be determined in several ways. As the heading is derived from attitude information, it can be calculated using three or more GNSS antennas. Usually the heading information is derived from a commercially available GPS-compass like the JLR-20 aboard the BS “MAINZ”. In this case three GNSS antennas spanning a triangle as large as possible (see Figure 7; note that the GPS-compass in the middle of the ship might had accuracy degradation due to shadowing effects) were set up. This resulting additional GNSS-compass is used for comparing reasons. The main properties of both systems are given in Table 3.

Table 3: Compared GNSS-Compass Systems

	PiloNav-System	JRC JLR-20
Number of GNSS-antennas	3	3
baseline lengths	2 x 20.3 m; 1 x 4.0 m	0.45 m
Accuracy	not determined but expected better than the JLR-20	0.5° RMS

The GNSS-compass of our system uses the determination of the three baselines between the three antennas using double-differenced carrier phase observations. Several tests ensure that only highly accurate and reliable results are accepted. For example only baselines with a successful fix of the ambiguities are used and after a length-check of each, it is tested if congruence with the original triangle is achieved or not.

As a GNSS-independent reference of higher accuracy was not gathered during this measurement campaign, the following consideration is limited to a comparison of the two systems.

The difference of the determined headings from each of the systems is depicted in Figure 9. Values are only given if simultaneous results were available.

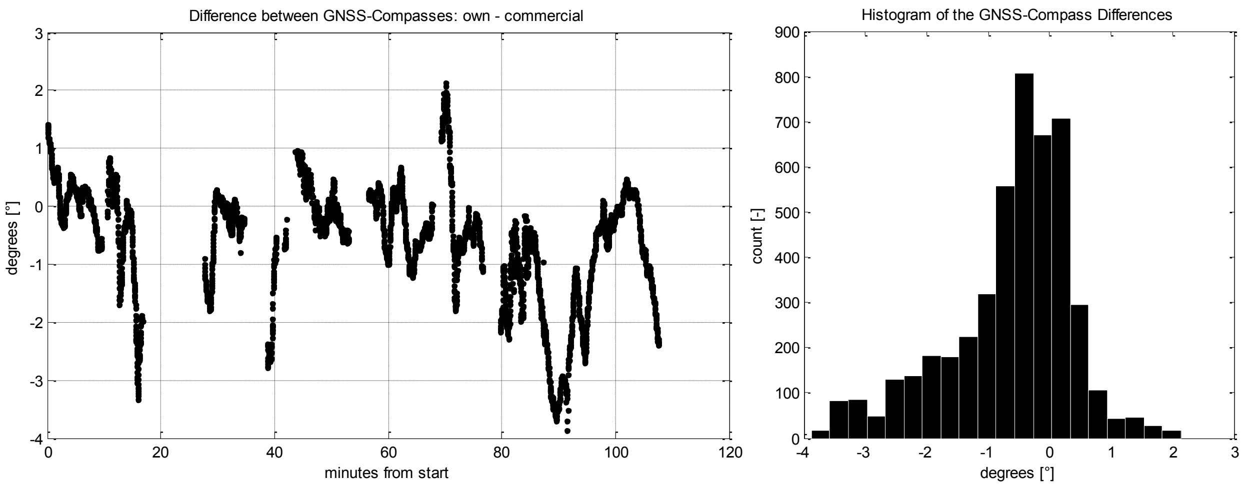


Figure 9: Differences between the two Systems that were used during the measurement campaign. (left: PiloNav GNSS compass vs. JLR-20, right: histogram of the differences)

It can be seen, that there is an offset present, most likely caused by the accuracy of the initial mounting of the commercial GPS compass. Assuming an uncertainty of one degree (according to the values of Table 4) in heading, a ship length of 40 m and a centrally installed GNSS compass means, that the bow or stern are not determined within around 35 cm.

Table 4: Values of the Heading Analysis

Average	-0.6°
Standard-Deviation	1.0°

Looking closer at the data derived by the commercial system during a longer berthing period gives more information of the performances of those systems. In Figure 10 it can be clearly seen that the GNSS compass realised with the three spread antennas represents a non-moving object quite well with only little variations while the commercial system shows unexpected changes. The decreasing and later increasing difference might indicate that the commercial system is quite constellation-sensitive.

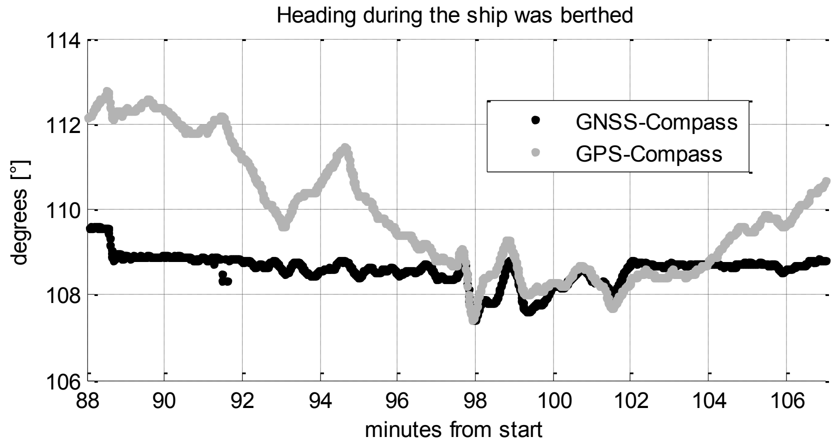


Figure 10: Differences between the two GNSS compass systems while the ship was berthed.

4.3. Heading determination in challenging conditions

Another source of heading information is the processing chain of the tightly coupled sensor fusion (see Figure 8). This processing chain uses averaged data from the IMU that is working at an output rate of 200 Hz. The averaging is done to reduce the noise and to achieve a data rate of 20 Hz in the subsequent processing, which is synchronised with the GNSS data rate. Especially in challenging areas regarding the quality and availability of GNSS signals a sensor fusion approach with inertial sensors is ideal to cover areas where the availability of one of the other sensors cannot be guaranteed but results are nevertheless crucial. Figure 11 shows the upstream passing of the three bridges as described in chapter 3.1. The outages of the GNSS compass due to the signal shadowing of the bridges can clearly be seen but also the capability of the IMU to continue to provide proper heading information.

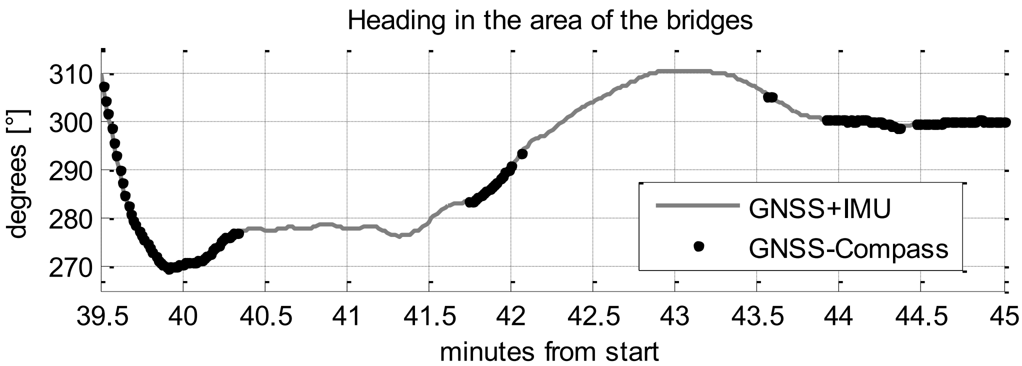


Figure 11: Availability of the GNSS compass in the areas of the bridges (Sector 2)

4.4. Manoeuver Guidance

Estimation of optimal routes, in the sense of minimising both time and effort required for a vessel going from its actual position to those belonging to the so-called "best practice" route of navigation, has become a critical task in inland water navigation not only by the need of saving resources but also for the further complications involved in this kind of environments. The presence of additional elements such as locks, bridges and quay walls in river corridors, poses an additional challenge for navigation and highlights the necessity to have efficient algorithms able to supply optimal trajectories while contributing with short-term risk collision detection.

In this regard, the availability of highly accurate PNT data based on GNSS/IMU sensor fusion provide a unique opportunity to investigate the determination of reliable trajectories in real-time, offering a wide range of maritime applications ranging from the precise docking manoeuvres to the efficient passing through lock chambers. For this purpose, a simple kinematic model based on the works presented in [4, 7] has been implemented and tested in different traffic conditions within the frame of the PiloNav project and is shown below.

4.5. Modelling Approach

To establish a model able to cope with the aforementioned requirements for optimised trajectories, the key criteria of minimising the course deviation with smallest control effort [4] has to be taken into account.

For analysis purposes, the vessel is considered to move only in the $N - E$ plane with the orientation defined by the Course over the Ground CoG - relative to the E axis. The vessel's speed is defined by its velocity *v* in the direction of the CoG, with the acceleration a pointing also towards this direction. Vessel's angular velocity is regarded as the so-called Rate of Turn r, $\dot{CoG} = r$. Hence, the optimisation problem can be written as:

Cost Functional: $\mathbf{min}_{t_f,a(t),r(t)} \left[\boldsymbol{c_1 t_f} + \int_{t_0}^{t_f} \left(\boldsymbol{c_2 a^2(t)} + \boldsymbol{c_3 r^2(t)} \right) \boldsymbol{dt} \right]$ (1)

with

State Variables: $\boldsymbol{y} = [\boldsymbol{N},\ \boldsymbol{E},\ \boldsymbol{v(t)},\ \boldsymbol{CoG(t)}]'$

Control Variables: $\boldsymbol{u} = [\boldsymbol{a(t)}, \boldsymbol{r(t)}]'$

Equation (1) shows how this simple model attempts to minimise time and effort by controlling sudden changes in velocity and CoG through the minimisation of a and r. More complex models including not only the 2D-kinematic of a vessel, but also its height component as well as environmental factors (such as currents and winds) should be considered to achieve results that are closer to the reality.

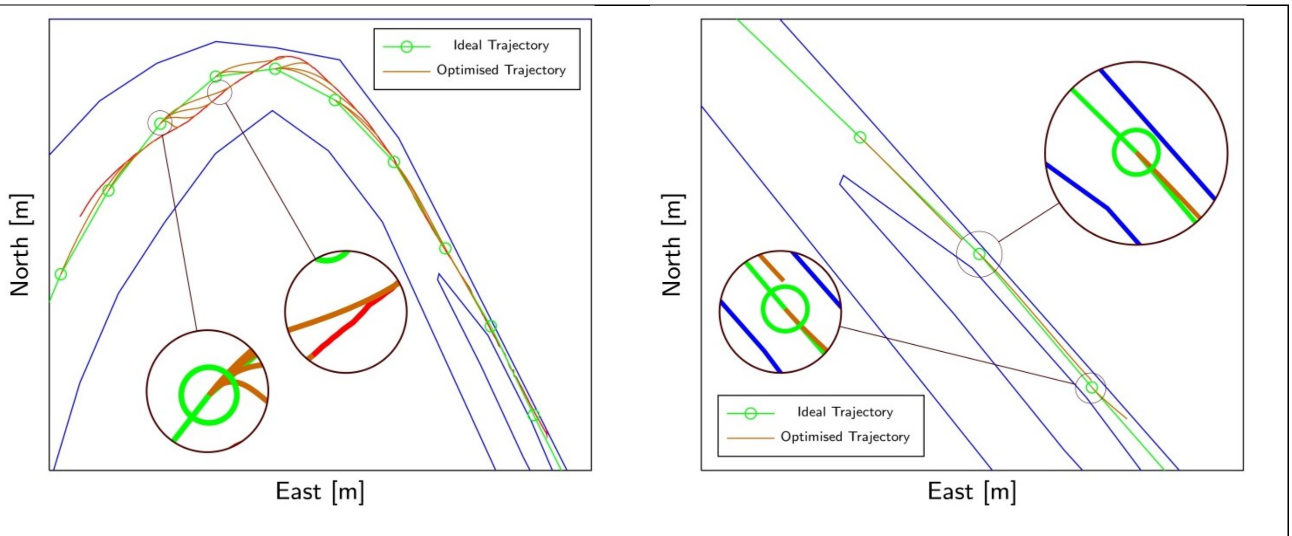
The proposed problem is solved using the optimal control problem solver OCP, which transforms the system into a nonlinear programming problem by parameterizing the control variables and approximating the cost functional, to then use the so-called sequential quadratic programming technique to solve the associated nonlinear programming problems [8, 9, 10].

4.6. Optimised Trajectories with PNT-Data

To evaluate the convenience and the numerical efficiency facing real-time data, the model discussed in Section 4.5. was tested in the demonstration area described in Section 3.

To do so, the most frequently followed trajectory - calculated as the average trajectory of those done by all the vessels sailing the channel over a period of one week - was set as the source of the final conditions for the optimised trajectories (green line in Figure 12). This ideal trajectory, in the form of equidistant way points, is therefore used to establish the final coordinates and final *CoG*s - regarded as the direction between two consecutive way points - at each stage of the navigation within the river corridor.

Under these assumptions the following scenario is proposed: it is required to find the optimal trajectory that will move the vessel state from $[E_k, N_k, v_k, CoG_k]'$ to $[E_w, N_w, v_k, CoG_w]'$ minimising time, acceleration and rudder movements. Here the subscripts *k* and *w* stand for Koblenz data and the closest way point. In this case, it was assumed that the final velocity will be equal to the initial one.



(a) General Overview **(b) Lock Chamber Detail**

Figure 12: Optimised Trajectories for Koblenz Data

Figure 12 shows a sample of the solutions for the proposed scenario. The actual trajectory of the vessel (red line) provides the initial conditions for the definition of the optimisation problem while, as it has been said, the ideal line (green line) supplies its final conditions.

Orange lines represent each one of the multi-stage optimised trajectories composed by a set of states which take the vessel from its origin point to its destination together with the (minimum) time to accomplish the manoeuvre. It goes without saying that the calculated trajectories follow the desired path while minimising effort and time for the navigation, but also it is worth to mention that the performance of their solution is applicable for near-real-time applications due to the low latency of its solution: 2-4 seconds per point, relatively high for real-time applications such as the PiloNav manoeuvre guidance system (Table 5).

Table 5: Parameters of the solutions

	Sample Point							
	1	2	3	4	5	6	7	8
Terminal Time	53.5	34.6	31.4	30.8	38.3	29.8	36.4	35.4
Solution Time	2.86	3.85	2.50	2.40	1.45	1.32	2.30	3.009
No of Iterations	56	106	92	59	55	51	50	82

5. Conclusion and Future Work

This paper gives an overview about the inland water aspect of the project PiloNav, which scope is the provision of validated methods for rail and inland-water traffic in order to provide precise and reliable dynamic data (PNT data), an efficient assistance to navigation of vessels and traffic management (manoeuvre optimisation) as well as detection and avoidance of collision risks.

In critical scenarios, such as bridge crossing, in particular radio navigation systems are error prone and subject to signal disturbances such as multipath and shadowing. These effects can complicate an accurate and reliable position determination by global navigation satellite systems (GNSS), e.g. GPS. Therefore the GNSS-based system is augmented by an inertial measurement unit in order to guarantee the continuous determination of accurate PNT-data.

As this is a work in progress paper, this article presents preliminary results using the example of the heading determination based on real measurement data as input for a manoeuvre guidance system. The PNT-side future work will be the fine tuning of EKF-parameters in order to using the full potential of the GNSS/IMU sensor fusion. Then, additional ship-borne sensors, such as Rate of Turn Indicator (RoTI) and Radar, will be integrated in order to enhance the robustness and reliability of the final system. The performance of manoeuvre guidance system has to be evaluated and to be improved to ensure its usability in a real-time environment.

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