Probabilistic Integration of GNSS for Safety-Critical Driving Functions and Automated Driving—the NAVENTIK Project

Robin Streiter, Johannes Hiltscher, Sven Bauer and Michael Jüttner

Abstract The NAVENTIK project will develop an automotive platform for computational demanding applications in the field of sensor data fusion and software defined radio. Based on this platform, the first component launched will be an automotive-grade GNSS (Global Navigation Satellite System) receiver that integrates state-of-the-art signal processing for lane level accurate navigation and that guarantees bounded false alarm rates. This is possible, thanks to a software-defined approach and the probabilistic integration of GNSS signal tracking algorithms on radio level. The explicit modelling of GNSS error sources and local signal degradation provide the basis for the proper Bayesian integration. The project will enable the first mass-market GNSS receiver based on a software-defined approach that is able to meet safety-critical requirements as it copes with false alarm specifications and safety related requirements.

Keywords GNSS · Localization · Automated driving · Safety requirements · Functional safety

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1 Introduction to GNSS in Automotive Applications

The steadily increasing grade of automation in modern vehicle's driver assistance and automated driving functions has a considerable impact on the development of all subsystems involved. This applies especially to the functions derived from sensor data fusion and environmental perception, as the compliance to functional safety and false alarm specifications is hard to prove and guarantee. One approach to cope with these demanding requirements is the consistent modelling of the system from a probabilistic perspective, which includes signal-processing operations, the propagation of uncertainties, fusion of heterogeneous sensor data and the representation of the system state. This results in the so-called Bayesian framework as the fundamental basis for advanced signal processing that, if applied consistently, can satisfy false alarm specifications and safety issues by nature.

The NAVENTIK project provides a key enabling technology to leverage satellite based navigation for automated maneuvers and safety critical decisions in automotive applications. A combination of innovative low-level probabilistic signal processing algorithms will be implemented within a software defined GNSS receiver, in combination with advanced high-level data fusion approaches in order to derive a confidence estimate that is able to meet any safety requirements in urban areas.

There are different approaches that are able to detect multipath affected GNSS observations. An overview of these so-called Multipath Mitigation algorithms is given in [1]. A straightforward approach is identifying multipath by considering digital maps with modelled 3D buildings in order to validate the direct line of sight to each satellite. In the Bayesian framework, this approach is used to predict multipath affected GNSS observations [2]. Another algorithm for determining non-line-of-sight (NLOS) with the help of environmental knowledge is described in [3].

The next group is of approaches is of significant interest as it uses statistic tests and probabilistic filtering for the identification and mitigation of multipath. A known representative in this category is the *Receiver Autonomous Integrity Monitoring* algorithm (RAIM) or an extension called Probabilistic Multipath Mitigation (PMM) [4]. From a probabilistic perspective, the PMM algorithm is of major importance as it was able to show the benefits regarding the improvement of the integrity in different safety relevant automotive use cases.

All these approaches are implemented on observation level and suffer from the GNSS receiver's proprietary signal pre-processing, which is supposed to be not stringent from a probabilistic point of view. To a huge extent remaining errors of multipath mitigation algorithms can be reduced by a reimplementation of GNSS signal processing under the prerequisite of a probabilistically consistent signal tracking.

The idea of signal manipulation on radio level is called Software Defined Radio (SDR). In general, this approach is to substitute signal processing hardware on radio level by a software implementation. This technology is very demanding in terms of computing power and data throughput but has high potential from scientific point of view as it allows a flexible implementation and validation of complex signal processing algorithms.

In the field of satellite-based navigation, it is called Software Defined GNSS. Complex algorithms like the a GNSS pseudorange error density tracking using a Dirichlet Process Mixture [5] or a Bayesian approach to multipath mitigation in GNSS receivers where implemented based on this technology. Another statistical signal tracking approach on this level with special consideration of tracking time-delays, amplitudes and phases is described in [6]. A Bayesian multisensor navigation, incorporating pseudorange measurements and a multipath model is presented in [7]. In order to meet these demanding computational requirements the NAVENTIK GNSS receiver will be implemented on an automotive grade system on chip that will be described in detail in the next chapter.

The NAVENTIK approach is to guarantee to not to discard any information, especially multimodalities in the measurement space. One major problem from multipath mitigation perspective is the evaluation of the auto correlation function for each satellite and the irreversible assignment of pseudoranges. The proposed approach uses the idea of a signal tracking implementation, as a derivative of probabilistic data association (PDA) in order to deal with the multimodal characteristics and outliers within the measurement space and to resolve these ambiguities within the Bayesian framework [8]. Thus, the NAVENTIK signal-tracking algorithm condenses multipath and NLOS effects as generic system properties and the Bayesian implementation improves the integrity of the system state in multipath and NLOS environments.

Figure 1 gives an illustrative idea of the integrity concept for one single point in time and its practical influence to applications are described in this chapter related to use cases. Figure 2 shows the metric of confidence within an urban scenario evolving over time. The blue plot represents the real 2-dimensional position error regarding the ground truth of the validation system. A reference GNSS System

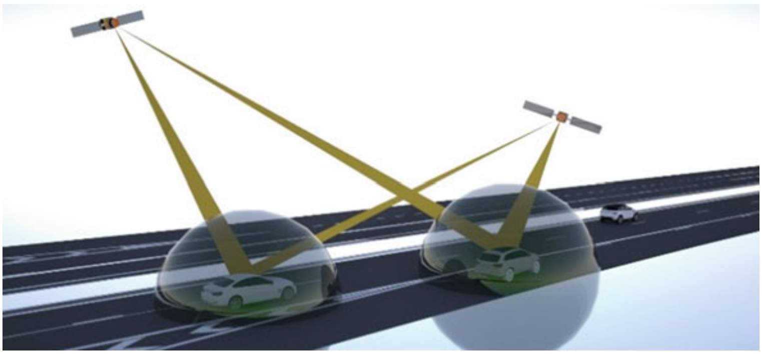

Fig. 1 High-level representation of the GNSS confidence level as a basis for safety-critical driving functions. The NAVENTIK GNSS receiver guarantees the vehicle is within the confidence level according to a given false alarm specification

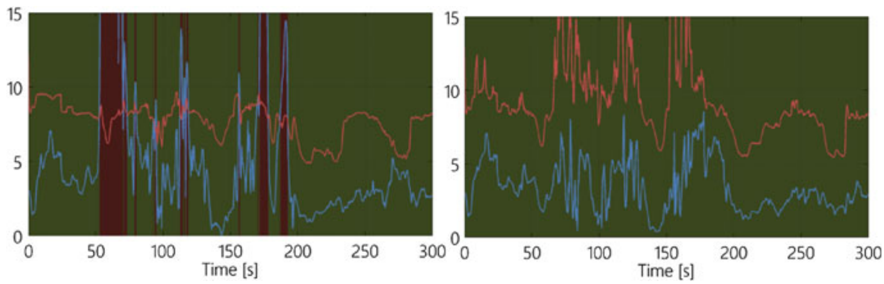

Fig. 2 Integrity of positioning data is guaranteed when the confidence interval (*red line*) covers the real position error (*blue line*). The *left* plot shows the violation of the integrity concept with a classical GNSS receiver. The *right* plot shows the result of the proposed system for the same situation without any disruption. Next to the improved positioning accuracy, the confidence measure is not violated

consisting of a Novatel Span with Real Time Kinematic and Inertial Measurement Unit provides the ground truth with a position accuracy within cm-level. The red plot shows the estimated confidence interval of the position. In the example, the confidence interval is set to 3σ, which means 99 % of all position candidates are supposed to be within the confidence interval. The left diagram shows a traditional GNSS receiver with average performance in an urban scenario. Next to the absolute position error (RMSE), it is evident that the assumption of 3σ integrity is not met at all. Areas where the true position error exceeds the estimated confidence results in a corrupted position estimate. The red areas shown in the diagram indicate those situations. Therefore, the traditional GNSS receiver is not legitimate for usage in safety critical applications. In contrast to the traditional receiver, the right diagram gives an indication about the performance of the NAVENTIK receiver, which will be implemented on the software-defined platform. On the one hand, the real 2-dimensional positioning error is improved due to the advanced signal tracking implementation and on the other hand, the estimated confidence covers the true position error for the entire sequence. This is the prerequisite for using the GNSS receiver in a safety critical context. Starting from this approach, we can computationally proof, that the GNSS receiver can meet dedicated false alarm specifications of a safety critical application.

This approach is a step towards the applicability of low cost satellite navigation for safety relevant applications in the automotive area, as it enables the computation of a reliable confidence interval even under degraded GNSS signal reception situations.

Unfortunately, the algorithms resulting from this strategy are demanding in terms of data throughput and computational power. Thus, the implementation on electronic control units (ECU), if possible at all, requires a very complex adoption process. Therefore systems-on-chip (SoC) are more and more in the focus for the integration in ECUs, as they can provide huge capacities especially for demanding signal processing operations by employing DSPs (digital signal processor) and FPGAs (field programmable gate array) along with a flexible and reconfigurable system design and operating system.

2 Confidence Adaptive Use Cases

Figure 1 gives an indication about the estimated confidence interval that is provided by the NAVENTIK receiver. According to given false alarm specifications, the NAVENTIK system can guarantee the true position of the vehicle to be within the given confidence interval, which is represented by the sphere around the vehicles. Derived from this information a couple of use cases will be introduced within this chapter.

2.1 E-Call Extension

In case of an emergency situation, E-Call 2.0 activated by the involved vehicle sends information related to the accident to the emergency call center like speed level right before accident, number of passengers, damage report and a warning to surrounding vehicles. As the NAVENTIK system provides extended information about the position, especially about the likely distribution about affected roads, lanes and directions dedicated actions can be taken into account. The NAVENTIK receiver delivers the trusted and high integrity position information to enable E-Call to submit the precise location of the crashed vehicle. The following figure shows the additional information of the NAVENTIK system:

2.2 Active Navigation

Currently, navigation and routing is the strongest use case for GNSS in automotive mass-market applications. In the light of recent developments towards more integrated and automated driving, the consequent exploitation of GNSS for automated driving functions is expected as a prominent use case. Active navigation focuses on the realistic performance and requirements for an efficient exploitation of the NAVENTIK key technology. As an extension of the strongest and common applications, the NAVENTIK contribution towards the robust integration of GNSS data into safety critical driving functions has a huge potential from mass-market perspective Fig. 3.

Furthermore, active navigation does not rely on the penetration or existence of aiding technologies like communication or infrastructure and an implementation can be tailored to available technologies and resources. Derived from the generic

(a)

(b)

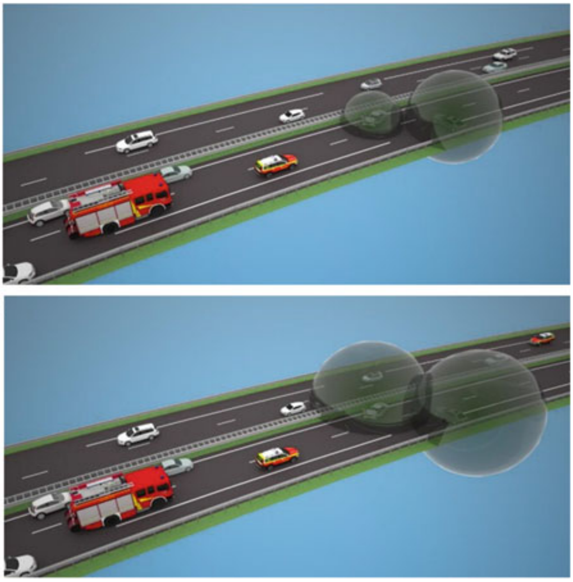

Fig. 3 **a** The confidence of the position estimate is high. The cars can be assigned to the road where the accident has happened and an ambulance can be sent in the correct direction on the highway. **b** The confidence of the position estimate is low and the position of the vehicles cannot clearly be assigned to the driving direction. Maybe it is helpful to send an ambulance for each direction to make sure no detour and additional time is needed

NAVENTIK approach, of integrating GNSS within any safety critical context, active navigation is a special implementation of this idea with the focus on a strong market potential with a very short time-to-market. The further development of conventional routing and navigation towards a more integrated and active assistance approach will leverage the awareness of GNSS based automated driving functions and passive navigation systems can be easily extended towards an automated mode, that reflects the current positioning performance and adds different modes of automation.

Figure 4 shows the extension of the classical "passive" navigation use-case to Active Navigation. If the accuracy of the position reflects lane or road level performance, the navigation system supports the driver with additional active steering and automated acceleration.

With decreasing performance, the degree of automation reduces accordingly, which means the steering wheel indicates only subtle and soft steering motions and driving instructions. The further limitation of the performance related with a very low confidence forces the system to switch back to conventional, uncritical turn-by-turn instructions. Finally, if GNSS is not available, the system gives very

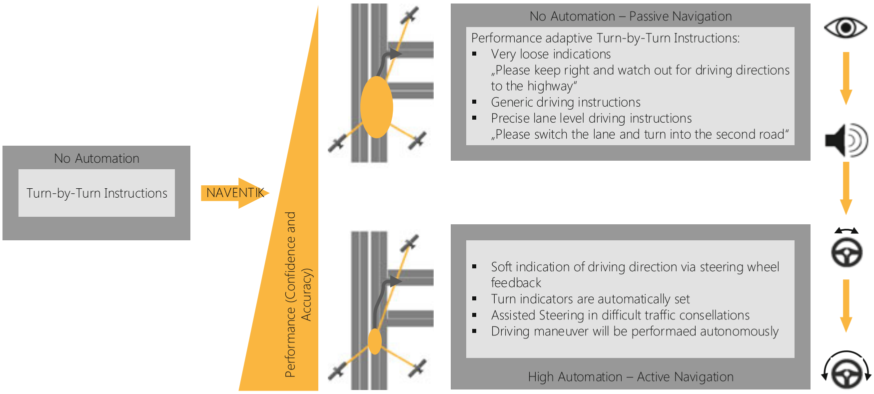

Fig. 4 Extension of the legacy navigation and routing application. Classical navigation systems do not offer any level of automation. Thanks to the confidence information, the system adopts different levels of automation depending on the positioning performance

rough estimations about the driving direction, only. That means the system can also influences the user acceptance by dramatically reducing the false alarm rate, not only in the safety critical context.

3 NAVENTIK Measures and System Architecture

The basic system architecture proposed is shown in Fig. 5. The positioning task is partitioned to a hardware and a software component. The hardware component will be implemented using FPGA resources; logic components are shown as squares and

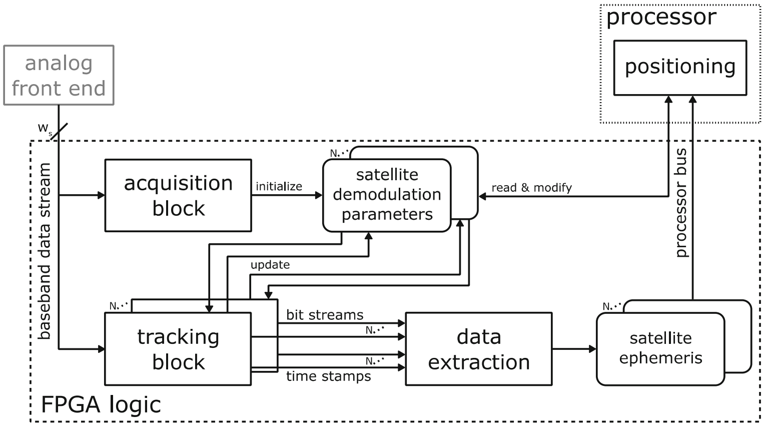

Fig. 5 NAVENTIK project system architecture

memory elements as rounded boxes. Carrier and code acquisition and tracking will be implemented as hardware blocks as they involve computing intense operations like Fourier transforms. The highly parallel FPGA hardware allows such functionality to be implemented very efficiently and with high throughput. Using fixed-point arithmetic the required functionality can be mapped to FPGA hardware efficiently.

Acquisition and tracking blocks work in concert, using the incoming sampled data stream from the analog frontend. The acquisition block continuously monitors the input data to detect newly available satellites. To increase resource efficiency only one acquisition block will be implemented which sequentially scans the different satellite codes. When the block has locked to a satellite's signal, it hands over the determined initial demodulation parameters (carrier frequency and code phase) to a tracking block, which adapts the demodulation parameters if necessary and extracts the transmitted bit stream. Each tracking block is capable of handling one satellite's signal. The tracking block also converts the high-speed sampled baseband data stream from the analog frontend to a low speed, oversampled bit stream. As the block is implemented using configurable hardware it can be modified to implement and study different mechanisms for multipath compensation addressing data demodulation. To compensate for processing delays, the tracking blocks also generate data collection time stamps required for pseudo range computation.

The data extraction block processes the demodulated data streams generated by the tracking blocks; it locks to the frames sent by the tracked satellites, checks whether data frames were received correctly and finally extracts the ephemeris data and inserts it into a data structure. One data extraction block is sufficient for processing the data received from all satellites in sequential order as the data streams have a very low speed.

The positioning algorithms, however, are not implemented in FPGA logic as they involve floating point logic and transcendental functions. Such operations are more conveniently handled by a general-purpose processor (GPP), shown in the upper right corner of Fig. 5. This can be an integrated processor as found in modern Programmable Systems on Chip (PSoC; e.g. Xilinx Zynq or Altera Cyclone/Arria devices); a processor IP-Core implemented using FPGA resources or even a distinct embedded processor. We consider implementing these algorithms on a GPP advantageous as software implementations are more flexibly adapted than hardware implementations and post processing—like probabilistic filtering–can be added and changed very easily to study the effects of different approaches. Ephemeris data extracted by the GNSS hardware blocks is accessible to software via the processor's memory map, which it is accessed via an interface to the processor peripheral bus. The architecture also allows the positioning software to alter the demodulation parameters, which are also memory mapped. This allows the software to alter settings and parameters of the tracking block, e.g. to change the precision of the code tracking unit.

Prospectively NAVENTIK aims at generalizing the proposed platform to enable software defined processing of arbitrary sensor data. This appears meaningful as sensors of any type usually perform internal pre-processing using fixed algorithms.

This is a necessary step to remove noise, distil the relevant information from the raw sensor data and reduce it to a manageable amount. Usually the pre-processing algorithm and its parameters are fixed within the sensor and not accessible by the user. We expect other types of sensors to benefit from adaptive statistical filtering in the same way as shown for GNSS. The mechanisms of sensor data filtering use a common set of algorithm building blocks which are numerically complex and computationally demanding, which hinders implementing them on common embedded hardware. To fill this gap, we aim at developing a more general version of the proposed GNSS SDR platform adaptable to a broad range of sensors.

Although the weak computational performance of embedded systems is tackled by integrating general-purpose programmable graphics processing units (referred to as GPGPU), there are strong reasons for employing a dedicated hardware platform for sensor data pre-processing. Sensor data pre-processing typically does not utilise floating-point spaces to their full capacity. Employing fixed-point hardware and a lower number of bits than provided by established floating-point standards can lead to implementations that are more efficient. Sensor data pre-processing employs a common set of functional blocks, which can be implemented as dedicated hardware elements, again altering processing efficiency. However, the biggest advantage over state-of-the-art general-purpose hardware is that a dedicated platform can provide hard real-time constraints, an important demand of safety-critical systems.

The proposed architecture of the proposed Software Defined Sensor system is shown in Fig. 6. The overall structure is similar to the system proposed for GNSS SDR. The hardware-software partitioning is identical; the complex pre-processing functionality is implemented as dedicated hardware. Based on the incoming raw sensor data stream (referred to as sensor baseband data), the hardware estimates initial settings for the first processing step, filtering and/or demodulation. This block extracts the relevant information from the incoming sensor baseband data and forwards it to the data generator. The data generator produces the actual

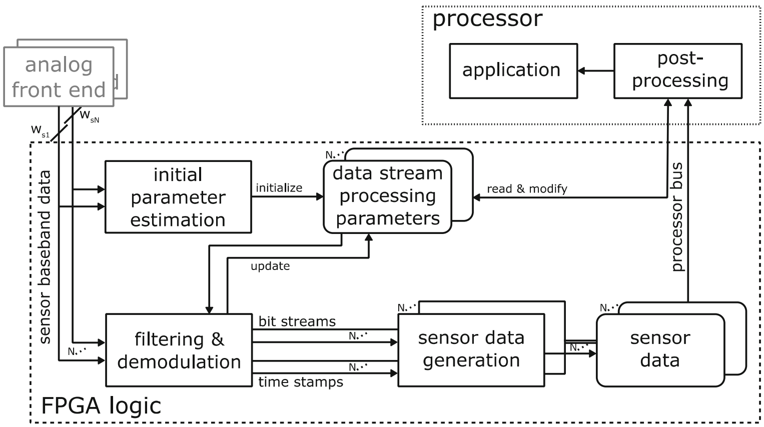

Fig. 6 Proposed system architecture of a general-purpose Software Defined Sensor system

measurements which can then be processed in software to alter flexibility. To be more general, sensor data processing is depicted as a post-processing step and the actual application working with the data. The post-processing step can include further, less demanding data refinement procedures. Furthermore, it can be used to assess the suitability of the automatically determined data stream processing parameters and adapt them if necessary. This enables applications to control the process of filtering the sensor baseband data, giving them the opportunity to adapt the mechanisms to varying environmental influences. We expect this approach to yield more precise sensor data by giving applications control over the pre-processing stage as they can integrate situational knowledge, leading to a situation aware tuning of pre-processing parameters rather than a fixed, good on average, model.

4 Conclusion

The NAVENTIK receiver is based on a software prototype that has been developed and verified in a wide range of use cases in the European research projects CoVeL (Cooperative Vehicle Localization) and GAIN (Galileo for Interactive Driving) within the 7th Framework Programme. The extension regarding confidence adaptive use cases in a safety related context will be implemented today, within the InDrive project in Horizon 2020. The NAVENTIK project is dedicated to the further development of the Prototype towards a mass-market product.

Starting from the software-defined approach for GNSS signal processing we are going to adopt a generalized platform design in order to complement requirements not only arising from the field of satellite navigation but also to extend the system by environmental perception sensors such as Radar and Lidar.

Those systems do also suffer from signal preprocessing which is, from a statistical perspective, always subject to strong losses of information. Clustering algorithms and noise reduction at the very early stage are violating the integrity of those sensors as well. Especially advanced tracking algorithms in nowadays ACCs (Adaptive Cruise Control) can benefit from the statistically correct representation within the measurement space especially where the weaknesses of existing systems, like tracking extended targets and obstructed objects are emerging. We can assume that tracking performance and overall reliability of those perception systems can be significantly improved by the proper integration within the NAVENTIK platform.

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