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Permanent Link to Sensing Location: Software Receiver Estimates Signal States During Outages

2021/06/09

By Hans-Georg Büsing, Ulrich Haak, and Peter Hecker Future safety-relevant driver assistant systems demand vehicle state estimations accurate enough to match the position within a road lane, which cannot be provided by standalone GPS. A promising approach to meet the requirements is the fusion of standalone or differential GNSS measurements with vehicle sensor data like odometers or accelerometers. To achieve deeper sensor integration, a software GNSS receiver was developed at the Institute of Flight Guidance (IFF) that is able to use dead reckoning sensors to support its signal acquisition. This article presents an approach to estimate the signal states during outages based on the tightly coupled vehicle state, which reduces the reacquisition time and significantly increases the signal availability. GNSS-based navigation is a key enabler for future advanced driver assistance systems (ADAS). Car manufacturers have identified automotive assistance systems as core devices to propose their uniqueness mainly in the luxury and upper-class market segments. While the precision and availability of loosely coupled single-frequency GPS navigation satisfies the requirements of typical route guidance systems, future automotive systems — especially those that enhance driving safety — are more demanding on positioning system performance. The Institute of Flight Guidance (IFF) of the Technische Universität, Braunschweig, Germany, is involved in two research projects evaluating the performance of unaided traditional GNSS receivers coupled with vehicle sensor measurements such as odometers in a tightly coupled architecture. Besides these involvements, the IFF has developed a general-purpose software-based GNSS receiver allowing full access to signal processing routines. The benefits of the tight sensor fusion are reliable state estimations even during total signal outages that are common in the automotive sector due to tunnels, parking decks, or urban canyons. In this architecture, the GNSS receiver works autonomously to deliver raw GNSS-measurements only. Additional knowledge

provided by the vehicle sensors cannot be used to support the receiver in any way. Besides other beneficial aspects in the tracking channels, additional external knowledge about the vehicle state has the potential to reduce acquisition times and improve the measurement availability significantly. The Institute of Flight Guidance uses a software environment called “Automotive Data and Time-Triggered Framework” (ADTF) for research in the field of ADAS and automotive navigation. In this software framework, the overall system architecture is assembled with independent modules. These modules are implemented as libraries and loaded into ADTF. Data is exchanged via pins that are defined as public variables. The framework also attaches timestamps to the individual measurements and adds a data recording and playback functionality. From a general-purpose software GNSS receiver, presented at the ION GNSS 2010, we have derived an automotive-specific ADTF software receiver module. The software framework adds the flexibility to synchronously process measurements from vehicle sensors additionally to the IF data from the front end. This gives us the opportunity to aid signal processing in the software GNSS receiver with additional external sensors. For positioning, a tightly coupled positioning filter based on GPS raw data measurements and the rear-wheel odometers is implemented. The vehicle’s motion is modeled using a kinematic relationship between the vehicle sensors and the GNSS measurements. Based on the tightly coupled vehicle state estimation, an acquisition state is processed during signal outages that enables the software GNSS receiver to reacquire the satellite signal instantaneously with high precision. In this article, the constituent parts of the system are presented and the estimation of the acquisition state derived. The system was tested in an urban scenario, and the state estimations validated with the recorded measurements.

System Architecture The software-defined GNSS receiver developed by the IFF was designed to process the computationally expensive signal correlation on an Nvidia graphics board using the vast parallel processing capability of graphics processing units (GPUs). With the use of common graphics boards, an entire receiver can be implemented on an ordinary PC, needing only a front-end to receive digital GNSS signals in an intermediate frequency (IF) band. For research in the field of vehicle state estimation, a derivate of the software receiver of the Institute of Flight Guidance has been implemented in the “Automotive Data and Time-Triggered Framework” (ADTF). The software is commonly used in the automotive industry for the development of ADAS. Figure 1 shows a typical system layout in ADTF. A central component of the framework is the ability to record and play back measurement data, which is indicated by the buttons on the left of the screenshot. Figure 1. System Architecture in ADTF. (Click to enlarge.) Within ADTF, the systems are assembled from modules that are shown as blocks within the graphical configuration editor. Standard modules such as the connection of common hardware are provided with the framework. Custom modules can be implemented in C++ by the user. Every module is implemented as a dynamic library (DLL) and interpreted by the framework. Modules can be featured with input and output pins. These pins are implemented by using specific data types from the framework. The communication and data exchange between the modules is handled via these pins. They can be connected by graphically drawing connector lines in the configuration editor. ADTF provides the user with classes for timing and threading. Processes can thereby be linked to the ADTF system time, which is especially important as the data replay can

be slowed down or sped up for debugging. The instantaneous reacquisition algorithm is based on a traditional approach of tightly coupling GNSS raw data with vehicle sensor measurements. The fusion is based on a kinematic model following the Ackermann geometry establishing the relationship between the vehicle's motion and the respective measurements. At each time step of an arriving measurement, the vehicle's motion is predicted based on the last estimated state with an extended Kalman filter. The prediction is then corrected using either measurements from the vehicle sensors or GNSS raw measurements. The range and Doppler measurements are calculated in the tracking channels of the ADTF software GNSS receiver. The corrected vehicle state is then fed back into the kinematic model for the next update cycle. In case the GNSS signal is lost in a tracking channel, a virtual tracking channel is initialized with the last calculated channel states. The change in the channel output is then predicted utilizing the change in the vehicle state and the current evaluation of the ephemeris. The schematic implementation of the channel state prediction is shown in Figure 2. Figure 2. Schematic of Channel State Prediction. (Click to enlarge.)

Signal State Estimation Using the tightly coupled architecture presented above, an estimated position and velocity can even be provided during total signal outages. Assuming that the last valid observation of a satellite signal is stored together with its respective time to and position, an estimation of the signal state (that is, Doppler frequency, code- and carrier-phase) based on the estimation of the vehicle state during the signal outage at time t_1 can be used for an instantaneous signal reacquisition. Using the ephemeris data provided by the respective GPS satellite the range between a user position x_u and the satellite x_{sv} can be calculated using the following terms Δ (1) and (2) with $|\dots|$ indicating the Euclidian distance. Therefore the change of the range can be obtained with equations (1) and (2): Δ (3)

Assuming an unbiased Gaussian error distribution of the measurements, the tightly coupled system provides an estimation of the covariance matrix of the vehicle state. Using only the submatrix Δ (4) related to the vehicle position, the covariance of the user position along the line-of-sight to the satellite can be obtained with the Euclidean norm of the line-of-sight vector Δ (5) and the law of error propagation: Δ (6)

Furthermore, using the law of error propagation, it can be shown that the variance of the change of range estimation in equation (3) is obtained by: (7) With the last valid range measurement related to time t_0 , the signal state at time t_1 can be obtained for the pseudo-range PSR Δ (8) and the carrier phase Φ : Δ (9) The resulting variance of these estimations can be expressed by Δ (10) and Δ (11) respectively. The estimate of the Doppler and the related variance can be obtained analogous.

Considering the variances of the estimation, it can be decided if the signal can be reacquired instantaneously or if the receiver has to find the signal using standard acquisition routines in a limited search space.

Experimental Validation

The Volkswagen Passat station wagon operated by the Institute of Flight Guidance was used to evaluate the performance of the proposed algorithm (see PHOTO.) The test vehicle is customized from the standard by adding an additional generator to meet the power requirements of the measurement and processing hardware. In addition, the Controller Area Network (CAN) is mirrored and open to access the data collected by the sensors of the vehicle. The relevant sensors include a longitudinal accelerometer, a gyro for measuring the yaw rate as well as the odometers of all four wheels. The test vehicle is equipped with a GNSS front-end developed by the

Fraunhofer Institute for Integrated Circuits. It is capable of streaming L1, L2, and L5 RF samples via two USB ports. The sampling rate of L1 is 40.96 MHz at an intermediate frequency of 12.82 MHz. Test Vehicle. A customized Volkswagen Passat was used to evaluate performance of the algorithm. The vehicle sensor data is streamed via CAN to an automotive PC from Spectra. It is equipped with an Intel quadcore CPU, 8 GB RAM, a Vector PCI CAN device and 256 GB SATA solid state disk allowing up to 195 MB/s writing speed. Additionally, it has been equipped with an Nvidia GeForce GT 440 graphics board that is used for processing the GNSS RF data. This specific graphics board was chosen because it offers a comparably high performance of the GPU at relatively low power consumption. Both GNSS RF data and data from the vehicle sensor network are streamed to an ADTF hard disk recorder. Due to the setup of the data acquisition, several challenges have to be solved. The first challenge is that the front-end needs to be used as hardware-in-the-loop. It is by itself not equipped with an automated gain control. Therefore, it is not possible to just stream the RF data but it has to be decoded, processed for adjusting the gain, and then stored to the hard drive. Secondly, the recording setup needs to cover high data rates. The GNSS front-end streams approximately 20 MB/s. As the data needs to be decoded and processed for gain control, the expanded data rate for recording is ~ 40 MB/s. In total including vehicle sensor measurements, >2000 data packets per second are streamed to the recorder. Because this could not be done using mechanical hard drives, we used solid state disks that also allow data storage during times of high vibration. Related to the before-mentioned challenges, an efficient thread management needed to be implemented. The software framework's threading classes are utilized to parallelize the receiver processes. Additionally, it has arisen that a significant part of the processing time is taken by the data transfer to the memory of the GPU. In order to prove the advantages of an odometer-aided reacquisition, an applicable testing scenario was chosen. To distinguish an odometer-based acquisition approach from a model-based approach, a trajectory was chosen that features a right turn of 90 degrees immediately after cutting off the GNSS signal. A model-based kinematic prediction would project the trajectory in the direction of the latest known heading derived by the GNSS solution. Only a sensor-based state estimation is able to resolve the right turn. The driven trajectory is shown in Figure 3. The GNSS signal has been cut off for approximately 10 seconds, which is equivalent of a 75-meter drive on dead reckoning sensors only after the right turn. Figure 3. Trajectory of test drive includes a 90-degree turn. (Click to enlarge.)

Results The following plots in Figure 4 show the performance of the virtual tracking channels. The plots in the upper row show the pseudorange output over time. For vividness they have been corrected for the motion of the respective satellite that is dominant due to their high speeds. Over a short period of time the satellites' motion relative to the receiver can be linearly approximated. The pseudorange measurements over time were fit using a linear regression. The respective value of the linear regression was then subtracted from the pseudorange and plot over time as shown in the figures in the second row, leaving only the approximated influence of the vehicle's motion. Figure 4. Modified pseudorange and Doppler results of the virtual tracking channels. (Click to enlarge.) The Doppler measurements have been similarly compensated by just subtracting the minimum measurement. These modifications of the pseudorange and Doppler measurements allow a direct

comparison of each other as the Doppler can be understood as the first derivative of the pseudorange over time. The results of PRN 6 show that the Doppler estimate during the GPS outage smoothly fits into the surrounding measurements without any major outliers. The plot of the pseudorange shows a similar behavior. The pseudorange could have potentially been modeled using a dynamic prediction that is not based on vehicle sensors due to the limited dynamics on the pseudorange measurements. The Doppler plot of PRN 16 shows a strong change in the relative velocity between satellite and receiver. If a further projection of the Doppler using a linear dynamic model would have been used instead of predicting with vehicle sensors, it would likely have misled the reacquisition by ~ 50 Hz. The trend in the pseudorange measurements is comparable to PRN 6 at a higher rate of change. The plots of PRN 21 probably show the advantages of using vehicle sensors for reacquisition best as the dynamics on pseudorange and Doppler are the most significant in the group. Both pseudorange and Doppler show a turning point during the GNSS outage. Especially, the pseudorange would have been mismodeled using a kinematic prediction that is not relying on additional sensors.

Conclusion In this article, a tightly coupled positioning system implemented in the automotive-specific framework ADTF was presented that is based on the fusion of standard automotive sensor data and software receiver measurements. We showed that, using the tightly coupled solution, an acquisition state during signal outages can be estimated that allows the tracking channels to reacquire the signal instantaneously without the need of computationally expensive acquisition routines. Under the assumption of a tightly coupled RTK position and small outage times, a reacquisition of the carrier phase without losing the information about the phase ambiguity seems possible. In the next version of the automotive GNSS receiver, the authors are planning to integrate the vehicle sensors to aid the tracking loops, which is likely to further improve tracking continuity especially in scenarios with high vegetation. Additionally, we plan to show that the implementation is capable of working in real time. Improvements of the initialization of the virtual tracking loops are also intended.

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