Development of a GNSS Based High Accuracy Measurement System to Support Vehicle Dynamics Testing

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Abstract

The article presents the development of a low-budget positioning device that aims to provide an alternative in self-driving vehicle development research that could replace costly, commercially available devices. In addition to being financially advantageous, it has the added benefit of allowing students to be involved in development. The primary function of the device is the sensor fusion, which outputs position, velocity, and orientation estimation based on data provided by Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) technology and an Inertial Measurement Unit (IMU). High-frequency estimates are generated by running an Extended Kalman Filter (EKF) on a microcontroller in an embedded environment. During the work, new challenges arose several times that required solutions. For example, delays due to the operation of GNSS receivers, which the estimation algorithm must compensate, and proper calibration of the sensors for the measurement vehicle. In addition to the software, the development of the tool includes the complete design, manufacture, and testing of the hardware, which allows testing the completed software units not only in a simulation but also in a real environment. During testing, the output of the developed device was compared several times with commercially available hardware for similar purposes.

Keywords: GNSS, IMU, Kalman filter, low-cost, positioning, RTK

1 Introduction

Nowadays, with the growing interest in autonomous vehicles and the ever-increasing number of new developments, there has been a need for high-precision measurement of the dynamic condition of cars. This may include monitoring the current position, accelerations, velocities. Many products on the market already meet these requirements, but their usage can be an exclusionary reason in many cases due to high prices. There are solutions for applying smartphones for similar topics [1], which can spare the custom hardware design and production cost. The disadvantage, which excludes this solution, is the inaccuracy of GNSS positioning.

In [2], the proposed algorithm is an Extended Kalman Filter with 15 states, which also includes errors regarding the inertial sensor and GNSS data to maximize the prediction accuracy. The publication also mentions the use of a vehicle wheel odometer which can be a viable option for our case in the future.

In [3], the authors approached the problem in a different way. There are tightly coupled techniques to integrate GNSS and INS sensors to provide more accurate information. In this case, the algorithm is based on the raw GNSS measurements, for example, pseudorange and Doppler observables. This approach offers better accuracy in poor signal and limited coverage scenarios.

Even if the GNSS data are integrated with other information like INS or odometry, the measurements can be inaccurate in urban canyons surrounded by high buildings. In [4] a unique method is proposed, which uses a fish-eye lens camera to observe the visibility of the sky and the satellites. Based on this information, they can decide the weighting factor of the used sensors during prediction.
The purpose of this publication is to illustrate the hardware and software architecture of a device capable of producing high-precision, high-frequency position, velocity, and orientation data. The main goal is to use less financial material than its commercial counterparts with loosely-coupled GNSS and INS sensor integration.

2 RTK GNSS device

2.1 Hardware

The hardware comprises several different modules to implement the desired functions. It includes two u-blox GNSS receivers, an IMU sensor, a microcontroller, LEDs, and various communication interfaces like CAN and USB ports. For said hardware elements to work together as a unit, designing a printed circuit that implements the expected circuit connections between the components is necessary.

The central microcontroller is a 32-bit ARM Cortex-M7 controller with a maximum clock speed of 300 MHz, providing sufficient resources to receive, process, and communicate sensor data. In addition to the essential functions, it has several interfaces, such as UART ports, SPI, I2C, or CAN communication capabilities typical of automotive controllers. This way, sensor data can be read out at high frequencies and transmit raw and calculated data to other external devices simultaneously.

Two u-blox GNSS receivers on the hardware provide accurate position, speed, and orientation information. They support RTK technology, meaning they can produce data with up to 2 centimeters accuracy. It requires correction data provided by an external base station. A single receiver would be sufficient to determine position and speed, but a second device is necessary to determine high-precision orientation even in a stationary position. In this case, the heading is calculated from the relative position of the two antennas. The GNSS device of choice supports this feature, so it does not need to be implemented separately on the microcontroller.

For the device to estimate the required states of a vehicle, a Bosch BMI085 IMU sensor has also been placed on the circuit. It is a 6-degree-of-freedom sensor that includes a 3-axis gyroscope and a 3-axis accelerometer. The sensor can provide data with a maximum frequency of up to 2000 Hz, depending on the built-in filter configuration. The microcontroller communicates with the sensor via an SPI interface.

A fundamental requirement for a device intended for an in-vehicle environment is to communicate with other ECUs via the CAN network so that they can properly access the data it provides. The hardware is able to send some basic information about its status and, of course, publish raw GNSS and IMU data, as well as Kalman filter estimates with a 100 Hz update.

Fig. 1 The GNSS module (left) and the GSM module (right) hardware.

2.2 Software and challenges

The primary function is to predict high-frequency speed, position, and orientation data. The sensor data processing required for this takes place on a microcontroller with ARM Cortex M7 architecture.
Fig. 2 Sketch of the prediction data flow

Fig. 2 also shows the calculation is done by an EKF [5], which can determine the device's exact position, speed, and orientation with knowledge of the high-precision 8 Hz GNSS and 100 Hz IMU data.

The state-space consists of 10 parameters (1). The first four are for the orientation, represented in quaternion form. The next three are the latitude, longitude, and height for the position, and the last three are the velocity in NED coordinate system. In the future, it can be expanded by new ones if needed.

\[
[q_0 \ q_1 \ q_2 \ q_3 \ \text{posN} \ \text{posE} \ \text{posD} \ \text{velN} \ \text{velE} \ \text{velD}]
\]  

There have been several challenges during the development that significantly affect the accuracy of the estimates. One such factor is the fundamental property of GNSS receivers. Calculation of the centimeter-accurate information with RTK correction takes time, ranging from 50 to 100 milliseconds based on tests. Due to this delay, the position delay can be multiples of 10 centimeters in a high-speed scenario. Based on the outputs of the GNSS receivers, this delay is measurable, so by modifying the Kalman filter accordingly, this can be compensated. Fig. 3 shows the estimator already gives an accurate result.

Fig. 3 Raw 8 Hz GNSS position (with blue) and delay compensated predicted position based on GNSS and IMU (with orange)

The prediction accuracy also depends on the calibration of the IMU, which has two types. The so-called static calibration is required to determine and compensate the accelerometer and gyroscope biases and scale errors. The other is the relative orientation of the IMU sensor frame to the vehicle chassis frame, requiring rotational sensor data transformation. Most of these parameters can be calculated by a PC application, which is also under development.

One basis for the operation of the EKF is to use lower frequency but more accurate GNSS data to clarify the error of the data estimated from the IMU. The orientation around the vertical axis is determined from the positions given by the two antennas of the GNSS modules, but the exact values of pitch and roll are unknown. The calculation of these can be examined with the help of the IMU gyroscope, but this estimate may become more and
more inaccurate over time due to the noise and inaccuracy of the sensor. The development to solve this issue is currently running and being tested.

3 Correction module

RTK GNSS correction requires correction data from an external base station with a well-known location. The information can be transmitted through a wireless internet connection or radio communication. In this case, the internet connection is the appropriate way because there are several online services available nowadays. Furthermore, the Faculty of Civil Engineering is operating and testing GNSS base stations at the Budapest University of technology and Economics and on the ZalaZONE Automotive Proving Ground.

The hardware for this task is a separate device from the GNSS module. A Quectel LTE modem is responsible for the mobile internet connection, which later can be replaced by a 5G compatible one. An 8-bit microcontroller performs the configuration of the modem and the data management. An RS232 port is available for transmitting the correction data to the GNSS module.

4 Results and conclusion

During development, it was possible to compare the results of current improvements with a commercially available device developed for a similar purpose (iMAR iNAT-M200). In these tests, for example, we validated the results of the already mentioned delay compensation. In Fig. 4, it can be seen that the self developed position estimation (orange) fits the iMAR position prediction output (purple). Based on the more significant delay of the raw position, we assume that the GNSS chipset used in the iMAR is older than the ZED-F9P. The output of the presented device has more noise and corrections when a new GNSS measurement is available, which is also perceivable on the plot. This originates from the IMU inaccuracy, which means that the next steps must be taken in this direction.

Furthermore, in collaboration with the Department of Automotive Technology, we had the opportunity to perform a successful autonomously controlled double lane change during high-speed tests based on the signals from our device. We collaborate with the Faculty of Civil Engineering during the work, responsible for testing and configuring the base stations.

In the current phase of the work, it can be said that the performance meets the expectations. In the following, the main goal is to improve the performance by decreasing the prediction error from several different sources and increasing the reliability based on test results and user feedback.

![Fig. 4 Position delay comparison in the function of time.](image)

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