USING LOW-COST MEMS 3D ACCELEROMETER AND ONE GYRO TO ASSIST GPS BASED CAR NAVIGATION SYSTEM

Pavel Davidson[1], **Jani Hautamäki**[1], **Jussi Collin**[2]
Tampere University of Technology, Finland
Tel: +358 3 3115 11, e-mail: pavel.davidson@tut.fi

Abstract

Key words: MEMS inertial sensors, extended Kalman filter, land vehicle navigation

This paper presents the development of GPS based navigation system for portable devices at Tampere University of Technology. The objective was to develop a fully integrated system using MEMS inertial sensors with price range of US$ 10-15 for the set of inertial sensors combined with low-update rate GPS measurements. This system doesn’t require vehicle installation and can be easily transferred between vehicles. The approach uses 3D accelerometer and one gyro for directional measurements to improve GPS performance in terms of availability and reliability in weak signal environment and during short GPS signal outages. Loosely coupled extended Kalman filter provides optimally tuned navigation solution and continuous auto calibration of inertial sensors. The system accuracy performance was investigated by using land vehicle tests in real urban environment.

Introduction and overview

GPS based car navigation systems are very common nowadays. They are usually integrated into mobile consumer devices such as GPS-based peripherals and handheld GPS navigation devices, mobile phones, PDAs, or into automobile in-dash navigation systems. The commercial applications of these navigation systems can be location based servers, asset tracking devices and fleet management systems.

Performance of such navigation systems is greatly dependant on GPS position accuracy. There are some instances when GPS signals are not available: for example in tunnels or underground parking garages. In urban environment GPS signals can be also very weak or affected by multipath. In this case the position accuracy derived from GPS receiver might be lower than required. To improve GPS performance in terms of availability and reliability in weak signal environment and during GPS signal outages it is common to use external sensors such as accelerometers, gyroscopes, odometers, doppler radars etc. This article presents the development of GPS based car navigation system integrated with 3D MEMS accelerometer and one MEMS gyroscope. Ideally, GPS/INS integrated system requires measurements from IMU that includes three accelerometers and three gyroscopes. But most of high-volume mobile consumer devices and commercial applications are so cost-sensitive that the cost reduction while using only one gyro instead of three can be crucial for marketing success of these products. It can be also noted that odometer is not used in this system since it requires additional car installation which is not really possible from user point of view since this system is intended mainly for mobile consumer devices.

This paper shows how reduced order IMU (three accelerometers and one gyroscope for directional measurements) can be integrated with GPS receiver. The real time prototype is build upon Fastrax software development kit (SDK)[1] that includes Atheros GPS receiver [2], 3D VTI MEMS accelerometers (bias instability approximately 0.2 mg@60 sec integration time) [3], and one Analog Devices MEMS gyroscope (bias instability approximately 0.1 deg / sec@60 sec integration time) [4]. The integration algorithm is based on Kalman filter using loosely coupled algorithm. Fastrax SDK was chosen because of two rearosons: it enables convenient real time data fusion between GPS and inertial sensors outputs; it uses Atheros GPS chipsets that are optimized for low power consumption which is one of the most important requirements for mobile phones.

Major goal of our integrated system is improving GPS based car navigation system performance for the following cases: bridge brief up to 30 seconds GPS outages, deliver continuous and smooth 5 Hz output of

---

[1] MSc, researcher
[2] PhD, senior researcher

position, velocity and heading, filter out bad GPS position and velocity measurements. This article also refers to the problems of using only one gyro in real environment. Using only one gyroscope, for example, makes it impossible to properly account for the road grade.

System configuration

In this project, one low-cost Analog Devices ADXRS150 yaw-rate gyro [4] and VTI Technologies SCA3000 3D accelerometer [3] were selected as the dead reckoning sensors to augment Fastrax IT03 L1 GPS receiver [1]. Sensors are mounted on a separate sensor board which is connected to IT03 via SPI bus available on I/O card terminal connectors. Programming of the algorithm that fuses GPS and inertial sensor measurements was performed using the evaluation and software development kit (SDK) made by Fastrax Inc. shown in figure 1.

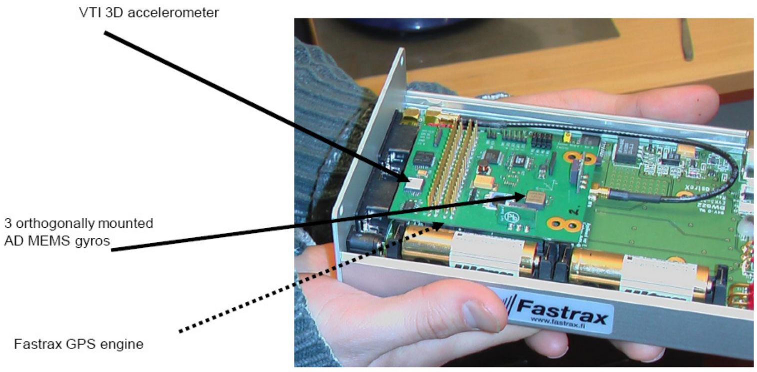

Figure 1: Fastrax evaluation and software development kit

Sensor board contains a 16-bit analog-to-digital converter (ADC) that samples the gyro output and then sends it to the SPI bus. The 3D accelerometer is directly connected to the SPI bus. The IT03 module performs both calculating the GPS solution and time tagging of the inertial sensor measurements.

The custom software consists of two different concurrent tasks: sampling task and EKF task. These tasks communicate to each other using the iTalk messages. The iTalk message is an interprocess communication method offered by the SDK. Sampling task reads the SPI bus and samples the inertial sensors outputs. Measurements are sampled at 100 Hz and then averaged over 100 millisecond interval. This averaged inertial sensor measurements is sent to the EKF task using the iTalk messages. Averaging is done in order to reduce excessive message flow since each message requires some of the system computational resources. The averaged inertial measurements are received at EKF task which is responsible for propagating the filter after new message arrives. The EKF task also receives the GPS solutions as a part of the iTalk messages from the built-in GPS navigation task.

Since the GPS position and velocity solution arrives once per second the EKF task can calculate the observation update once per second. The integrated GPS/IMU solution is sent at 5 Hz to the built-in NMEA task. This task converts the solution into NMEA format that can be read from the serial output of the evaluation kit.

The system components are connected as shown in Figure 2. In this arrangement GPS receiver is the core of the system and is responsible for both making its own measurements, and for time tagging of the inertial sensor measurements.

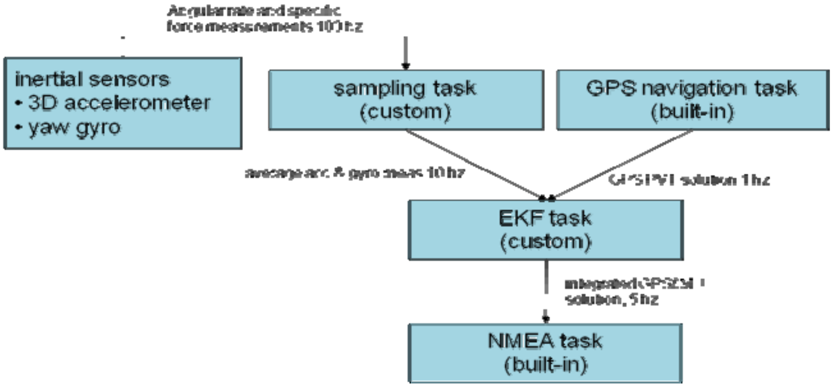

Figure 2: Fastrax SDK block diagram: data flow between the GPS receiver, inertial sensors, and the host computer

Integrated system components

MEMS sensor selection

The overall objective of the research presented in this paper is to develop a navigation system that costs $10-15 while achieving the accuracy requirements for land vehicle applications. The ADI MEMS gyro and VTI MEMS 3D accelerometer were selected for its low cost, small size, and good performance relative to others in its class. The specifications of the sensors are given in Table 1. Using this sensors selection, the total hardware cost of the IMU is about $15 (in bulk purchases), which meets the objective of the research.

	ADI ADXRS150 Gyro	VTI SCA3000 Accelerometer
Range	±150 deg/sec	±2 g
Non-linearity	0.1 % FS	±1% FS
Axis-misalignment	1 deg	3%
Turn-on bias	1 deg/sec	20 mg
Bias instability* (100 sec)	0.01 deg/sec	0.1 mg
Scale Factor error	1%	1%
Noise	0.05 deg/sec/√Hz	3 mg@45 Hz (RMS)
Bandwidth	40 Hz	45 Hz
Size	7x7x3.6	7x7x1.8 mm
Temperature range	-40°C - +85°C	-40°C - +85°C

Table 1: ADI gyro [4], and VTI accelerometer specifications [3]

* The bias instability was calculated using Allan deviation

The error model for accelerometers and gyro

The voltage output from the gyro is proportional to angular rate, and the voltage output from accelerometer is proportional to acceleration. These voltage outputs are sampled at 100 Hz by the A/D converter, and averaged by 10 samples to give an average heading rate and acceleration over the interval. Due to their light weight and fabrication process, the MEMS ADI gyroscopes and VTI accelerometers have relatively large uncertainty and cross-axes sensitivity (non-orthogonality of axis) compared to tactical grade IMUs. The performance of such sensors is also strongly affected by temperature variations. These factors affect the obtained accuracy of the navigation solution in the integrated systems, especially when GPS signals are not available.

The major source of dead reckoning solution errors is caused by sensor biases and gravitational forces because of unknown road tilts. The effect of sensor scale factor error and cross-coupling errors on dead reckoning solution is not so significant. Therefore the gyro output model consists of true vehicle heading rate (ω) plus a bias ($\delta\omega$) and a white sensor noise (w_{gyro}):

$$\omega_{meas} = \omega + \delta\omega + w_{gyro} \tag{1}$$

The sensor noise is assumed to be normally distributed with zero mean and variance

$$E\{w_{gyro}^2\} = \sigma_{gyro}^2 \tag{2}$$

The gyro bias is modeled as a first order Markov process driven by white noise:

$$\dot{\delta\omega} = -\frac{1}{T_g}\delta\omega + w_{g\_bias} \tag{3}$$

Assuming that the noise driving the bias is normally distributed with zero mean and variance

$$E\{w_{g\_bias}^2\} = \sigma_{g\_bias}^2 \tag{4}$$

The accelerometer measurement error includes a bias (δa) and a white sensor noise (w_{acc}). The accelerometer bias is modeled as a first order Markov process driven by white noise:

$$\dot{\delta a} = -\frac{1}{T_a}\delta a + w_{a\_bias} \tag{5}$$

Assuming that the noise driving the bias is normally distributed with zero mean and variance

$$E\{w_{a\_bias}^2\} = \sigma_{a\_bias}^2 \tag{6}$$

The dead reckoning algorithm utilizes the body frame longitudinal acceleration. This acceleration is integrated to obtain speed over ground which is further integrated to obtain distance traveled. Body frame longitudinal acceleration is composed of all three accelerometer measurements transformed from sensor frame to pseudo vehicle frame. It also includes the effect of gravitational forces because of unknown road grade. It is defined by

$$a_L = \ddot{x} + b_L + g \cdot \theta + w_{acc} \tag{7}$$

Where $\ddot{x}$ is the longitudinal acceleration, g is the gravitational constant, θ is the road grade and b_L is the longitudinal acceleration error.

The error model for GPS

The position accuracy of a single frequency L1 GPS receiver is approximately 10 m in the horizontal axis and 15 m in the vertical axis. A single frequency L1 GPS receiver determines velocity based on the Doppler shift of the GPS carrier wave. The velocity accuracy in the horizontal axis can reach 2-5 cm/s and in the vertical axis 4-10 cm/s 1-σ standard deviation of the stochastic errors [9][10]. The accuracy of GPS strongly depends on satellite geometry and multipath errors. The output rate of Fastrax GPS receiver is 1-5 Hz. In this project the update rate of 1 Hz was used to reduce computational burden on the DSP processor. The GPS velocity measurements can be also used to determine vehicle heading. If there is no vehicle sideslip the heading can be calculated as the arctangent of the east and north GPS velocity measurements:

$$\psi_{GPS} = \arctan\left(\frac{V_{GPS}^{east}}{V_{GPS}^{north}}\right) \tag{8}$$

The standard deviation of the heading error can be approximated by [12]

$$\sigma(\psi_{GPS}) = \frac{\sigma(\delta V_{GPS})}{V_{GPS}} \tag{9}$$

The GPS heading ψ_{GPS} is calculated only when a vehicle has sufficient speed. This threshold is determined empirically and in the current project is equal to 2 m/s.

Implementation of the Kalman Filter

The real time data fusion algorithm employs an extended Kalman filter (EKF) to combine computed GPS position, velocity, and heading with the acceleration and heading rate measurements provided by the dead reckoning sensors (3D accelerometer and heading gyro). Some independent filters were also used to calibrate the accelerometers and gyroscope, and estimate the sensor frame orientation with respect to the vehicle. The EKF uses the values of the filter states to predict the future states through a dynamic model which is based on dead reckoning method to estimate position and velocity. The EKF is necessary because the dynamic model is not linear. Since the degree of non-linearity in navigation applications can be high, the linearized Kalman filter can easily become unstable. Great care must be taken in choosing the necessary statistics to prevent divergence of the filter while maintaining adequate performance.

In the EKF, the dead reckoning errors are updated by the difference between GPS and dead reckoning solution. The nominal dead reckoning equations are as follows [6]

$$\frac{d}{dt}\begin{bmatrix} P_N \\ P_E \\ V_N \\ V_E \\ \psi \end{bmatrix} = \begin{bmatrix} V_N \\ V_E \\ a_x \cos\psi - a_y \sin\psi \\ a_x \sin\psi + a_y \cos\psi \\ \omega \end{bmatrix} \tag{10}$$

Where P_N, P_E, V_N, V_E are the north and the east positions and velocities, ψ is the vehicle heading, ω is the measured heading rate, and a_x, a_y are the measured accelerations in vehicle frame.

The non-holonomic constraint can be applied to further improve the navigation performance. Non-holonomic constraints refer to the fact that unless the vehicle jumps off the ground or slides, the velocity of the vehicle in the plane perpendicular to the forward direction is almost zero. The algorithm makes use of the constraint on vehicle dynamics directly, as opposed to using the non-holonomic constraint as measurements in a Kalman filter. It should be noted that if there is no vehicle sideslip the vehicle course is the same as vehicle heading. Using the linear error model the resulting state equations of the indirect Kalman filter are as follows

$$\frac{d}{dt}\begin{bmatrix}\delta P_N\\ \delta P_E\\ \delta V_x\\ \delta V_y\\ \delta\psi\\ \delta\omega\\ \delta a_x\\ \delta a_y\end{bmatrix}=\begin{bmatrix}0&0&\cos\psi&-\sin\psi&(V_x\sin\psi-V_y\cos\psi)&0&0&0\\ 0&0&\sin\psi&\cos\psi&(V_x\cos\psi+V_y\sin\psi)&0&0&0\\ 0&0&0&0&0&0&1&0\\ 0&0&0&0&0&0&0&1\\ 0&0&0&0&0&1&0&0\\ 0&0&0&0&0&-1/T_g&0&0\\ 0&0&0&0&0&0&-1/T_a&0\\ 0&0&0&0&0&0&0&-1/T_a\end{bmatrix}\begin{bmatrix}\delta P_N\\ \delta P_E\\ \delta V_x\\ \delta V_y\\ \delta\psi\\ \delta\omega\\ \delta a_x\\ \delta a_y\end{bmatrix}+\begin{bmatrix}0\\ 0\\ n^{acc}\\ n^{acc}\\ n^{gyro}\\ n_b^{gyro}\\ n_b^{acc}\\ n_b^{acc}\end{bmatrix} \quad (11)$$

The states of the EKF includes: north and east position, north and east velocity, heading, two states for acceleration measurement errors and misalignment, and gyro bias. The states for acceleration measurement errors were modeled as a Markov 1st order process. Since only one heading gyro is used the road tilt influence on horizontal acceleration measurements can't be separated from the actual vehicle acceleration. Nevertheless if the driving noise and time constant in Markov process are chosen correctly the total acceleration measurement error including road tilts can be approximated quite well by this model. Compared to the bias error and unknown road tilts, the effect of the scale factor error is relatively small. Therefore they are not included in the state vector. The KF error state vector is an 8-state vector. It was verified by numerous road tests that when GPS signals are available the integration algorithm for GPS + DR sensor measurement is robust to sensors bias variations and to moderate road tilts.

Taking the North and East position and velocity, and heading difference between GPS and DR the measurement equation is given by

$$z=\begin{bmatrix}1&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0\\ 0&0&1&0&0&0&0&0\\ 0&0&0&1&0&0&0&0\\ 0&0&0&0&1&0&0&0\end{bmatrix}\begin{bmatrix}\delta P_N\\ \delta P_E\\ \delta\psi\\ \delta V_x\\ \delta V_y\\ \delta\omega\\ \delta a_x\\ \delta a_y\end{bmatrix}+\begin{bmatrix}\delta P^{GPS}\\ \delta P^{GPS}\\ \delta V^{GPS}\\ \delta V^{GPS}\\ \delta HDG^{GPS}\end{bmatrix} \quad (12)$$

One way to improve the performance of integrated system for land vehicle navigation is to include the zero velocity update (ZUPT). During ZUPT the sensor frame misalignment can be updated. Gyro bias can be also calibrated during ZUPT mode.

System alignment and calibration

The difference of this integrated system from regular GPS receiver is that it has to be initialized before use. The initial alignment procedure includes the estimation of the sensor frame orientation with respect to the local level navigation frame, accelerometer bias and misalignment estimation, and also gyroscope drift estimation. This alignment procedure takes about 20 seconds and it can be done automatically. During and after this alignment procedure the navigation system (mobile phone, pocket PC) has to be fixed into cradle.

There are three coordinate frames that are used in this system:

- Sensor frame in which the sensors are mounted. The sensitivity axis of accelerometers and gyro are aligned with this frame.
- Pseudo vehicle frame [8]: X axis corresponds to longitudinal axis of vehicle, Z axis corresponds to vertical axis of the local level, and Y axis completes the triad.

– Navigational frame: local level North, East, Down (NED) frame. The dead-reckoning computations as well as GPS measurements are performed in this frame.

There is also intermediate “yawed” frame [8] which is the rotated sensor frame in such a way that the vertical axis matches the local level vertical. Initial alignment of this system consists of two steps: leveling and yaw angle estimation. Leveling is the estimation of pitch and roll angles between sensor frame and NED or “yawed” frame. These angles are estimated when vehicle is stationary based on accelerometer measurements. It should be noted that uncompensated parts of accelerometer biases are also included in these angles. The pitch and roll angles are used to calculate the transformation matrix between sensor frame and “yawed” frame. When vehicle is moving with constant direction the yaw angle can be also estimated. These pitch, roll and yaw angles are used to calculate the transformation matrix from sensor frame to pseudo vehicle frame.

When vehicle is stationary the gyro bias can be also estimated because in this case changes in heading are caused by gyro bias. The estimation algorithm is based on recursive least squares. This estimated value of gyro bias is subtracted from the raw heading rate measurements.

Experimental results

The system was tested in road tests in real driving environment that included tunnels, parking garages, urban canyons, and road interchanges. Typical performance during these road tests is presented in this section. Blue dots in the figures 3-4 correspond to the GPS position measurements. Red dots for the trajectory on the map correspond to the dead-reckoned (DR) computed position. When GPS signals are available the DR solution is combined with GPS. Figure 3 shows the system performance during 30 sec GPS outage. This GPS outage was made artificially by unplugging GPS antenna from the receiver. The maximum cross-track error was 60 m, and the maximum along-track error was 50 m.

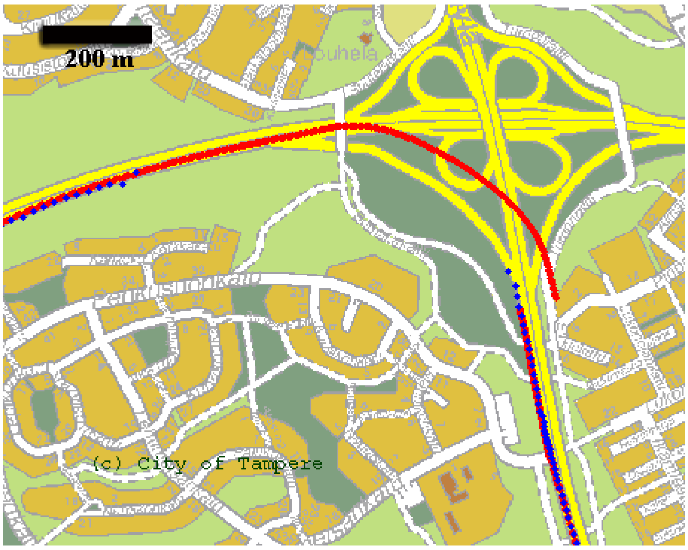

Figure 3: System performance during 30 sec GPS outage

Figure 4 shows the system performance during another 40 sec GPS outage. The maximum cross-track error was 30 m, and the maximum along-track error was 100 m. Quite large along-track error at the end of the outage was caused by the 2 deg road grade that was not measured by the inertial sensors and therefore unknown to the dead-reckoning navigator. This is the limitation of reduced-order IMU that have only one directional gyro instead of three required for accurate attitude measurement.

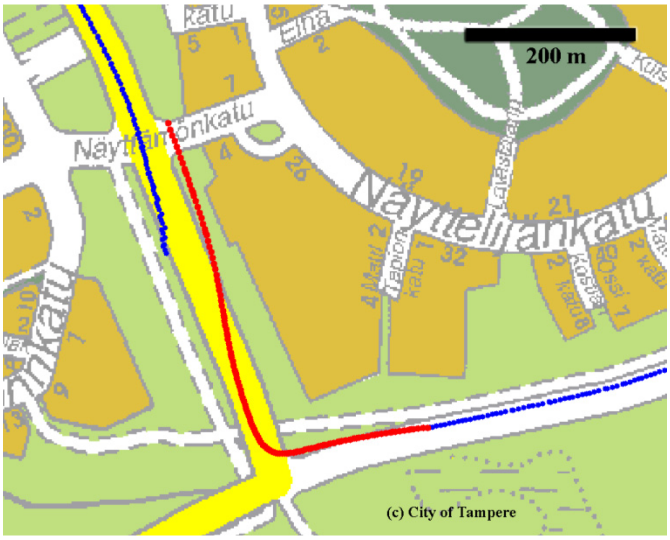

Figure 4: System performance during 40 sec GPS outage

Figure 5 displays the test route and for Seoul urban canyon drive test. This test route includes a 260 m long tunnel, marked as green rectangle,.and high-multipath urban canyon environment in the vicinity of high-rise buildings (30-40 storey buildings). Yellow lines show the GPS only solution, and red lines show GPS+MEMS system performance. It should be noted that there are no GPS signals in the tunnel. The first GPS measurements after the tunnel have large, about 100 m position error. Beginning of the tunnel is marked by lower arrow, and first GPS fix after the tunnel by upper arrow. This test shows significant improvement in position reliability of the combined GPS+MEMS algorithm by continuing to deliver accurate vehicle position, velocity, and heading in absence of GPS signal. This test also shows improvements in combined system performance in high-multipath environment which is explained by the combined GPS+MEMS algorithm ability to filter out GPS position and velocity outliers.

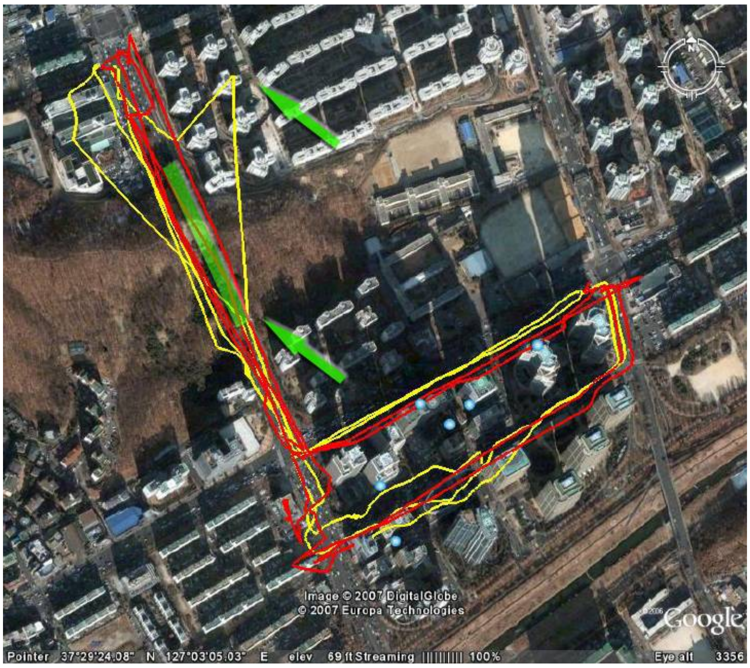

Figure 5: Urban test drive in Seoul, Korea

Conclusions

This paper has shown how low-cost inertial sensors can improve GPS position availability by continuing to output position during short GPS outages with the accuracy that is sufficient for most of the car navigation applications. The integrated GPS+MEMS system has also demonstrated improvements of GPS position accuracy in high multipath urban canyon environment by filtering out GPS position and velocity outliers. In addition this integrated system can provide 5-10 Hz output of the vehicle heading. This can be useful if map matching techniques are used. The experimental results have also shown that the unknown road grade can be the largest source of position and velocity errors during GPS outages. The performance of dead-reckoning only navigator is acceptable when the road grades do not exceed 3 deg.

It can be noted also that this device does not require installation in vehicle. It works in all vehicles and can be easily transferred between vehicles. Our future work will include comparison of the current integrated system which is based on GPS and reduced order IMU (three accelerometers and one gyro) with regular GPS / INS integrated system that uses six degree of freedom IMU.

Acknowledgments

The work described in this paper was partially carried out in the project Future GNSS Applications and Techniques (FUGAT) funded by the Finnish Funding Agency for Technology and Innovation (Tekes).

References

[1] Fastrax Ltd., technical specifications of "*iTrax03 Development Kit*" http://www.fastrax.fi
[2] Atheros Communications, http://www.atheros.com
[3] VTI Technologies Oy, technical specifications of *"SCA3000-D01 3-Axis Low Power Accelerometer With Digital SPI Interface",* http://www.vti.fi/en/products-solutions/products/accelerometers/sca3000-accelerometers/
[4] Analog Devices Inc., technical specifications of *"ADXRS150 ±150°/s Single Chip Yaw Rate Gyro with Signal Conditioning",* http://www.analog.com/en/prod/0,2877,ADXRS150,00.html
[5] Kaplan, E.D., "Understanding GNSS: Principles and Applications, Artech House, 1996.
[6] Farrell J., and Barth M., "*The Global Positioning System and Inertial Navigation",* McGraw-Hill, New York, NY, 1999.
[7] Spilker, J.J. *Fundamentals of Signal Tracking Theory*. In : Global Positioning System: Theory and Applications, Vol. I. Progress in Astronautics and Aeronautics, Volume 163, AIAA, Washington, DC, 1996.
[8] Chowdhary M., Colley J., and Chansarkar M., *"Improving GPS Location Availability and Reliability by Using a Suboptimal, Low-Cost MEMS Sensor Set"*, ION GNSS 20th International Technical Meeting of the Satellite Division, 25-28 September 2007, Fort Worth,TX
[9] Lätti, J., H. Leppäkoski, J. Collin and J. Takala (2007) *"Accurate Velocity Determination Using GPS: A Comparison Between Three Stand-Alone Receivers",* Proceedings of ENC-GNSS 07
[10] Serrano, L., Kim, D., Langley, R.B., Itani, K. and Ueno, M., *"A GPS velocity sensor: How accurate can it be? - A first look",* ION NTM 2004, San Diego CA, pp. 875- 885. 2004.
[11] Collin, J., Lachapelle G. and J. Käppi (2002) *"MEMS-IMU for Personal Positioning in a Vehicle - A Gyro-Free Approach"*, Proceedings of GPS 2002, The Institute of Navigation, Alexandria, VA, pp. 1153-1161.
[12] Bevly D., *"Global Positioning System (GPS): A Low-Cost Velocity Sensor for Correcting Inertial Sensor Errors on Ground Vehicles"*, J. of Dynamic Systems, Measurement, and Control, June 2004, Vol. 126

Due to essential color usage in figures, pdf file of the paper is available at
http://www.tkt.cs.tut.fi/research/nappo.htm