Orientation estimation of an outdoor vehicle using inertial, magnetic and CP-GPS sensors

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Abstract: - The orientation estimation of an outdoor ground or aerial vehicle is crucial in an autonomous control system. The typical onboard sensors have disadvantages that makes hard to get reliable orientation based on a single sensor. This paper presents a state estimation system, which is able to collect the measurement data from inertial sensors, magnetic sensor and GPS receivers with carrier phase measurement capabilities. The system performs a real-time sensor fusion of the measured data using extended Kalman filters. The integer ambiguity problem and the correction is solved during the state estimation. The performance of the system is tested using real-time car tests.

Key-Words: - sensor fusion, carrier phase GPS, state estimation, inertial navigation

1 Introduction

The control of unmanned outdoor vehicles is in the focus of researchers in the recent decade. To establish a control system usually a reliable sensory and state estimation system is required. The tendency in the field of sensor manufacturing shows that the micro-electro-mechanical system based sensors have the reliability to operate as the sensors of low-cost state estimation systems. The applied sensors are the accelerometers and angular velocity sensors.

On the other hand these sensors has disadvantages, their offsets are usually significant but not known.

In vehicle navigation one of the basic sensors is the magnetometer. The magneto-resistance based sensors can be used in low-cost applications. The main problem with this type of sensor is that the Earth magnetic field is sometimes disturbed, even the chassis of the vehicle can produce distortion.

An other typical outdoor sensor is the GPS receiver. This is mainly used for the determination of the position of the vehicle. If the GPS receiver has the capability to measure the phase of the carrier signal, the accuracy of the sensor can be in a sub-decimeter range.

The most challenging problem of the carrier phase GPS approach is the integer ambiguity determination. This problem occurs because the integer number of carrier cycle between the satellites and the receiver is unknown. For the determination of the integer ambiguity different approaches are used. The typical solution is the LAMBDA method [1], but it usually needs some minutes of measurements to produce reliable result [2].

There are also methods which can determine the integer ambiguity only from one measurement. However, according to [3], the number of the false positive result of the single epoch methods can be high.

In spite of these disadvantages the carrier phase measurement based GPS navigation is already in commercial use in the field of harvesting [4] and land surveying [5],[6].

The general task of the state estimation systems in outdoor navigation is the determination of the kinematic state of the vehicle including position, orientation, velocity, angular velocity and acceleration.

This paper concentrates on the orientation part of the state estimation process. In our approach the offset (bias) of the inertial sensors are also considered.

The goal of our research is to produce a sensory system which can perform real-time and reliable state estimation and sensor fusion and uses low-cost sensors. Also an important factor is the size and weight of the whole module.

There are two main tasks where our system is planned to be used in the future. The first one is the identification of the non-linear dynamic model of airplanes. This project requires the data collection of
the sensors in real-time during test flights, but it is allowable that the state estimation is performed offline. The second task is the autonomous control of small scale car-like vehicles on rough terrain. In this case the data collection and the state estimation are required to run on the board of the vehicle in real-time. Therefore in the selection of the state estimation algorithms the computation capacity is important.

The structure of the paper is the following. In Section 2 the overview of the hardware structure of our system is presented. Section 3 introduces the problems of the carrier phase GPS approach based on the existing results of the literature. Section 4 describes the real-time state estimation and sensor fusion process. Section 5 presents the experimental results.

2 System overview
The structure of the system can be seen in Fig. 1. The central unit is an Atmel AT91SAM7A3 microprocessor, which is responsible for the synchronized data collection from the different types of sensors.

![System Diagram](image)

The time base of the data collection is provided by the main GPS sensors. This module has direct UART connection to the processor, providing position, velocity and ephemeris data. The raw carrier phase measurements of all the GPS receivers are propagated via an I²C bus.

The accelerometer is an Analog Devices ADXL330, sampled by 24 bit analog-digital converters. The angular velocity sensor module has three Analog Devices ADXRS613 sampled also with 24 bit analog-digital converters. The sensory system has a Freescale MAG3110 magnetometer which is connected to the I²C bus.

All of the collected and synchronized data are transmitted to an Atmel AT91SAM9XE ARM9 based microprocessor with 64 Mbyte SDRAM. This processor runs a real-time Linux operating system and it is responsible for the real-time sensor fusion. The module is equipped with an SD card for data logging and with an Ethernet interface for real-time monitoring.

This sensory system can be mounted on an outdoor vehicle. Fig. 2 shows an example in the case of a car.

The system has capability for three GPS receivers, but Fig. 2 shows only two receivers. This is because the presented sensor fusion algorithms in Section 4 require only two receivers.

The GPS receivers are fixed over the main axis of the car hence the vector between the two antennas (x_{rs}) shows the heading direction of the car. The inertial and magnetic sensors are mounted over the center of the rear axle. Their common coordinate system is K_S. The measured magnetic North direction is m_n. In the initial case when the vehicle does not move, the accelerometer measures the gravitational acceleration which is noted by g_d in Fig. 2.

![Car Diagram](image)

3 Carrier phase GPS background
The actual system has capabilities for three GPS receiver which are able to measure the actual phase of the carrier signal of a GPS satellite. In the recent solution raw measurement only from two GPS receivers will be used. Let \( \phi_r^i \) be the carrier measurement of the \( i^{th} \) carrier signal measured by the GPS receiver \( r \) in wavelength unit.

Using the theory of the carrier phase based GPS navigation [2], [5], [7], the double differenced equation can be used:

\[
\nabla \Delta \phi_{r,s} = (\phi_r^1 - \phi_s^1) - (\phi_r^1 - \phi_s^1)
\]
\[ \nabla \Delta \phi_{i,s} = \lambda^{-1}(e^i(t) - e^j(t))^T x_{r,s}(t) + 
+ \nabla \Delta N^{i,j} + \nabla \Delta \mu^{i,j}(t) \]  

(2)

where \( \lambda \) is the wavelength of the carrier signal, \( e^i(t) \) and \( e^j(t) \) are unit vectors pointing from the receivers to the corresponding satellite, \( x_{r,s}(t) \) is the position vector between the two antennas called baseline, \( \nabla \Delta N^{i,j} \) is a time independent constant called double differenced integer ambiguity and \( \nabla \Delta \mu^{i,j}(t) \) is a zero mean measurement noise.

The vectors \( e^i(t) \) and \( e^j(t) \) can be precisely calculated from the rough position output of the GPS receiver and the rough position calculation of the satellites using the transmitted ephemeris data. This information can be obtained from the main GPS receiver through the UART interface.

The double differenced integer ambiguity \( \nabla \Delta N^{i,j} \) can be considered as a time independent constant during a measurement interval where the carrier observables are obtained continuously both from satellite \( i \) and \( j \). Therefore in every case when a new satellite signal appears, the corresponding integer ambiguity should be determined.

Define the following vectors

\[ \nabla \Delta N = [\nabla \Delta N^{1,2} \ldots \nabla \Delta N^{1,m}]^T \]  

(3)

\[ \nabla \Delta \phi_k = [\nabla \Delta \phi_{k,1}^{1,2}(t_k) \ldots \nabla \Delta \phi_{k,m}^{1,2}(t_k)]^T \]  

(4)

\[ E_k = [e^i(t_k) - e^2(t_k) \ldots e^m(t_k)]^T \]  

(5)

\[ \nabla \Delta \mu_k = [\nabla \Delta \mu_{k,1}^{1,2}(t_k) \ldots \nabla \Delta \mu_{k,m}^{1,2}(t_k)]^T \]  

(6)

where \( m \) is the number of the visible satellites and \( t_k \) is the time of the \( k \)th measurement epoch. The satellite with the index 1 is called the master satellite. It is usually chosen based on the best SNR ratio or highest elevation angle to avoid the frequent change of the master satellite. Using these notations (2) can be written in the form:

\[ \nabla \Delta \phi_k = \lambda^{-1}E_k x_k + \nabla \Delta N + \nabla \Delta \mu_k \]  

(7)

where \( x_k \) is \( x_{r,s}(t) \) at time \( t_k \).

Equation (7) has \( m-1 \) independent scalar equations and \( m+2 \) unknown variables. The integer ambiguity vector has time independent property hence if \( \nabla \Delta N \) is known for the first epoch, the baseline \( x_k \) can easily be calculated for every measurement epoch.

### 4 State estimation

The input data of the state estimation are the measurements from the inertial, magnetic and GPS sensors. The inertial and magnetic sensors require calibration. The calibration method which was applied on the sensor data is described in [8] and [9].

The structure of the state estimation system is shown in Fig.3. This conception contains two extended Kalman filters. The input of the first level is the calibrated angular velocity and the calibrated magnetic measurement. The first output is an orientation estimation relative to the NED frame in quaternion form. The second one is the change of the orientation between the actual and the previous orientation of the sensor frame represented in the NED frame.

After the first EKF, a phase slip detection and correction block is applied. It uses \( \Delta \tilde{q}_{k,NED} \) to recognize a phase slip measurement error in the raw GPS data and correct it.

The second stage of the state estimation uses the output of the first level and the carrier observables of the GPS sensors. The output of the second level is a refined orientation estimation.

![Fig. 3. Sensor fusion structure](image)

The orientation of the moving vehicle is represented by unit quaternions. The definition of the quaternion is

\[ q = \begin{bmatrix} \sin(\alpha/2) \\ \cos(\alpha/2) \end{bmatrix} \]  

(8)

where the unit vector \( t \) is the axis of rotation and \( \alpha \) is the angle of rotation in radians. If a quaternion is known then rotation matrix can be calculated from the components of the quaternion using

\[ R = \begin{bmatrix}
q_1^2 + q_4^2 - q_2^2 - q_3^2 & 2(q_1q_3 - q_2q_4) & 2(q_1q_2 + q_3q_4) \\
2(q_1q_3 + q_2q_4) & q_1^2 + q_4^2 - q_2^2 - q_3^2 & 2(q_3q_2 - q_1q_4) \\
2(q_1q_3 - q_2q_4) & 2(q_3q_2 + q_1q_4) & q_1^2 + q_4^2 - q_2^2 - q_3^2
\end{bmatrix} \]  

(9)

Otherwise, if the orientation matrix is known then a quaternion can be formed from the rotation matrix by the following algorithm:
The initial orientation between $K$ and $z$ is the initial orientation between $K$ and $z$.

$$q_{~1} = \frac{R(3,2) - R(2,3) R(1,3) - R(3,1) R(2,1) - R(1,2)}{4d_1}$$

$$q_{~2} = \frac{R(1,2) + R(2,1) R(1,3) + R(3,1) R(2,3) - R(2,1)}{4d_2}$$

$$q_{~3} = \frac{R(1,2) + R(2,1) d_3 R(2,3) + R(3,2) R(1,3) - R(3,1)}{4d_3}$$

$$q_{~4} = \frac{R(1,3) + R(3,1) R(2,3) + R(3,2) d_4 - R(2,1) - R(1,2)}{4d_4}$$

### 4.1 State estimation – first stage

The aim of the first extended Kalman filter is to give the first approximation for the orientation between the sensor coordinate system and the North-East-Down coordinate system. The first stage is a sensor fusion between the angular velocity and the magnetometer measurements.

Using the kinematic of the moving body and derivative of a quaternion [10] the following discrete time model can be formed:

$$F(q_k) = \begin{bmatrix} q_{4,k} & -q_{3,k} & q_{2,k} \\ q_{3,k} & q_{4,k} & -q_{1,k} \\ -q_{2,k} & q_{1,k} & q_{4,k} \\ -q_{1,k} & -q_{2,k} & -q_{3,k} \end{bmatrix}$$

$$q_{k+1} = q_k + 0.5T_S F(q_k) \omega_k + v_k$$

$$m_{cal,k} = R(q_k)m_{cal,0} + z_m$$

where $m_{cal,0}$ is the measured magnetic vector during the initialization, $T_S$ is the sampling time of the inertial sensors, $\mu_q$ and $z_m$ are state and measurement noises and $R(q_k)$ is the rotation matrix in (9).

Forming the extended Kalman filter algorithm for this model, the algorithm has the following steps:

$$A_k = I_4 + \frac{1}{2}T_S \begin{bmatrix} 0 & -\omega_{3,k} & \omega_{2,k} & -\omega_{1,k} \\ \omega_{3,k} & 0 & -\omega_{1,k} & -\omega_{2,k} \\ \omega_{2,k} & \omega_{1,k} & 0 & -\omega_{3,k} \\ \omega_{1,k} & \omega_{2,k} & \omega_{3,k} & 0 \end{bmatrix}$$

$$Q_k = \begin{bmatrix} q_1 & q_2 & q_4 \\ q_2 & q_1 & q_4 \\ q_3 & q_4 & q_1 \end{bmatrix}$$

$$Q_k = \begin{bmatrix} -q_2 & q_1 & q_4 \\ q_1 & q_2 & q_3 \\ -q_4 & q_3 & q_2 \end{bmatrix}$$

$$Q_k = \begin{bmatrix} q_4 & -q_3 & q_2 \\ q_3 & q_4 & -q_1 \\ -q_2 & q_1 & q_4 \end{bmatrix}$$

$$C_k = 2Q_k(q_{k-1})m_0 Q_2(q_{k-1})m_0... Q_3(q_{k-1})m_0 Q_4(q_{k-1})m_0.$$

$$q_k = \tilde{q}_k + 0.5T_S F(q_{k-1}) \omega_k$$

$$\tilde{q}_k = q_k$$

$$M_k = A_k \Sigma_{k-1} A_k^T + R_v$$

$$G_k = M_k C_k^T (C_k M_k C_k^T + R_{\epsilon})^{-1}$$

$$\Sigma_k = M_k - G_k C_k M_k$$

$$\tilde{q}_k = \tilde{q}_k + G_k(m_{cal,k} - R(q_k)m_0)$$

where $R_v$ and $R_{\epsilon}$ are the covariance matrices of $v_k$ and $z_m$. It is usually a practical problem that the sampling frequency of the magnetometer is smaller than that of the inertial sensors. In a sampling period, when the magnetic measurement is not available, $\tilde{q} = \tilde{q}$ is used instead of (32).

The result of the state estimation is $\tilde{q}_k$ presenting the rotation between the initial orientation of $K_S$ (when $m_0$ was collected) and the $k$th orientation of $K_S$. The orientation relative to the NED frame can be calculated by $\tilde{q}_{S,NED,k} = R_{2q}(R(q_k)\tilde{R}_S,NED)$ (34) where $\tilde{R}_S,NED$ is the initial orientation between $K_S$ and $K_{NED}$ and operation $R_{2q}$ is the conversion of the rotation matrix to quaternion using (10)-(17).
\( \hat{R}_{S,\text{NED}} \) can be formed using the initial measurement of the accelerometer and the magnetometer.

\[
d_0 = \frac{a_{\text{cal}}}{\|a_{\text{cal}}\|}, \quad e_0 = \frac{m_{\text{cal}} \times d_0}{\|m_{\text{cal}} \times d_0\|}
\]

\[
\hat{R}_{S,\text{NED}} = [d_0 \times e_0] \cdot e_0 - d_0
\]  

(36)

The second level extended Kalman filter requires the rotation of \( K_{c} \) between the actual and the previous measurement epoch:

\[
\dot{\hat{q}}_{S,\text{NED},k} = \frac{e_{S,\text{NED},k-1} \circ \hat{q}_{S,\text{NED},k}}{R_{S,\text{NED}}}
\]

(37)

where \( ^{\circ} \) means the conjugate of the quaternion and \( \circ \) refers to the product of the quaternions [10].

4.2 Phase slip correction

A practical problem occurs by using GPS receivers which are able to measure carrier phase. This is the cycle slip problem. This means that the receiver cannot reliably detect zero crosses in the incoming signal. Therefore the measurement \( \nabla \Delta \phi_{k} \) suffers from an error, which value is an integer number of half cycles \((0.5 k, k \in \mathbb{Z})\).

The receivers are able to indicate the possibility of a cycle slip, but this does not mean a real slip, moreover its value is also unknown. Using additional information a detection algorithm is shown here. The additional information is the \( \Delta \hat{q}_{S,\text{NED},k} \) output of the first stage extended Kalman filter.

Let (7) be given for two consecutive measurement epochs of the GPS receiver \( k-1 \) and \( k \) and let us compose their difference. Using the notation

\[
\delta \nabla \Delta \phi_{k} = \nabla \Delta \phi_{k} - \nabla \Delta \phi_{k-1}
\]

\[
\Delta x_{r,s,k} = x_{r,s,k} - x_{r,s,k-1}
\]

(36)

(37)

an equation for the difference measurement can be given

\[
\delta \nabla \Delta \phi_{k} = \delta \nabla \Delta \phi_{k} = \lambda^{-1} E_{k} \Delta x_{r,s,k} + 2 \nabla \Delta \mu_{k}
\]

(38)

where it is assumed that the unit vectors directing to the satellites are almost the same in the two measurement epochs and the measurement noises have the same characteristics. The next step is to form an approximation for \( \Delta x_{r,s,k} \). First the change of the orientation between the \((k-1)\)th and \( k \)th GPS measurement epoch is calculated by:

\[
R_{k-1,k} = R_{2} q(\Delta q_{s}) R_{2} q(\Delta q_{s,i}) \ldots R_{2} q(\Delta q_{s,i})
\]

(39)

Where \( \Delta q_{s} \) is the first output of the first stage Kalman filter after the \((k-1)\)th measurement and \( \Delta q_{s,i} \) is the last one before the \( k \)th measurement. Then \( \Delta x_{r,s,k} \) can be approximated by

\[
\Delta \hat{x}_{r,s,k} = (R_{k-1,k} - I_{3}) \hat{x}_{r,s,k-1}
\]

(40)

where \( \hat{x}_{r,s,k-1} \) is the \((k-1)\)th result of (7) if \( \nabla \Delta N \) is known.

Forming the error

\[
\varepsilon_{\text{slip}} = \delta \nabla \Delta \phi_{k} - \lambda^{-1} E_{k} \Delta \hat{x}_{r,s,k}
\]

(41)

if its value is over a threshold, the cycle slip is detected and its value is proportional to \( \varepsilon_{\text{slip}} \). Hence \( \nabla \Delta \phi_{k} \) can be corrected.

4.3 Integer ambiguity search

Both the phase slip correction and the second stage Kalman filter requires the knowledge of \( \nabla \Delta N \). This value can be determined fast and reliably using the additional sensors on the board of the vehicle.

Let \( p_{s} \) and \( p_{r} \) be the position of the GPS receivers \( s \) and \( r \) in the sensor frame. This information can be determined during the assembly of the sensors into the vehicle.

An approximation for the baseline can be calculated by

\[
\hat{x}_{r,s} = \hat{R}_{ECEF,\text{NED}} R_{S,\text{NED}} \hat{T}_{K_{c}} (p_{r,S} - p_{s,S})
\]

(42)

where \( R_{ECEF,\text{NED}} \) is the rotation between the Earth-Centered-Earth-Fixed coordinate frame and the local NED frame. This rotation can be calculated using the position output of the GPS sensor [10], [11].

Using \( \hat{x}_{r,s} \) an approximation for the integer ambiguity can be formed:

\[
\nabla \Delta N = \nabla \Delta \phi_{k} - \lambda^{-1} E_{k} \hat{x}_{r,s}
\]

(43)

Around the approximated integer ambiguity a search space can be created which may contain the proper integer ambiguity. Let \( N_{\text{mins}} \) be used as a threshold value defining the search space for each scalar component of the integer ambiguity:

\[
\left| \nabla \Delta \hat{N}_{i,j} \right| - N_{\text{th}} \leq \left| \nabla \Delta N_{i,j} \right| \leq \left| \nabla \Delta \hat{N}_{i,j} + N_{\text{th}} \right|
\]

(44)

The proper ambiguity from the search space can be found using a criteria for the length of the possible baseline.

According to Fig. 2, the length of the baseline is fixed and known. Let \( L_{x} \) be the length of the baseline. The following minimum should be found in the search space:

\[
\nabla \Delta N = \arg \min_{\nabla \Delta N \in N_{\text{pos}}} \left( \left| E_{k} \nabla \Delta \phi_{k} - \nabla \Delta N \right| - L_{x} \right)
\]

(45)

where \( N_{\text{pos}} \) is the set of the possible integer ambiguities and \( ^{+} \) means the Moore-Penrose inverse.
As the result of the GPS based measurement calculation, the baseline in the NED coordinate system reads
\[ x_{r,s,NED} = \lambda R_{ECEF,NED}^T E_1^T (\nabla \Delta \phi_k - \nabla \Delta N) \] (46)

4.4 State estimation – second stage
In the first stage the orientation information is based on the magnetometer measurement. This direction vector has only partial orientation information about the full 3D orientation. In other words the orientation \( \vec{q}_k \) has uncertainty around the actual magnetic direction.

4.4.1 Estimation with fix number of satellite
In the first approach let us assume that the number of the elements of \( \nabla \Delta \phi_k \) is \( m-1 \).

The discrete time model between the orientation and the carrier phase observables including the phase slip error is
\[ q_{k+1} = A_k q_k + v_q \] (47)
\[ \nabla \Delta \phi_k = \lambda^{-1} E_k R_{ECEF,NED} R(q_k) x_S + \nabla \Delta N + \phi_{\text{slip},k} + z_\phi \] (48)
\[ \vec{q}_k = q_k + z_k \] (49)
where \( \phi_{\text{slip},k} \) is the actual value of the phase slip and \( x_S \) is the constant baseline in the sensor frame.

Based on the discrete time dynamic model the algorithm of the extended Kalman filter can be formed.
\[ A_k = \begin{bmatrix} \Delta q_{1,k} & \Delta q_{3,k} & -\Delta q_{2,k} & \Delta q_{1,k} \\ -\Delta q_{3,k} & \Delta q_{4,k} & \Delta q_{1,k} & \Delta q_{2,k} \\ \Delta q_{2,k} & -\Delta q_{1,k} & \Delta q_{3,k} & \Delta q_{4,k} \\ -\Delta q_{1,k} & -\Delta q_{2,k} & -\Delta q_{3,k} & \Delta q_{4,k} \end{bmatrix} \] (50)
\[ \partial R(q_k) x_S = \begin{bmatrix} Q_1(q_k) x_S & Q_2(q_k) x_S & \ldots & Q_4(q_k) x_S \end{bmatrix} \] (51)
\[ C_k = \begin{bmatrix} \lambda^{-1} E_k R_{ECEF,NED} \\ \partial R(\vec{q}_{k-1}) x_S \\ I_4 \\ \vec{q}_k = A_k \hat{q}_{k-1} \] (52)
\[ M_k = A_k \Sigma_{k-1} A_k^T + R_v \] (53)
\[ G_k = M_k C_k^T (C_k M_k C_k^T + R_z)^{-1} \] (54)
\[ \Sigma_k = M_k - G_k C_k M_k \] (55)

4.4.2 Handling the change of the satellites
If the number of visible satellites changes then the length of \( \nabla \Delta \phi_k \) vector also changes, hence the number of the rows of \( C_k \) will also change. This can be handled by using different size for \( R_z \). This covariance matrix can be chosen as
\[ R_z = \text{diag}(\sigma_\phi^2, \ldots, \sigma_\phi^2) \] (60)
where \( \sigma_\phi^2 \) is the variance of the carrier phase measurement.

The change of the visible satellites has effect on the integer ambiguities. If a satellite disappears the corresponding integer ambiguity can be removed from \( \nabla \Delta N \).

If a new satellite appears a new integer ambiguity can be calculated. In this case the actual estimation of \( x_{r,s,NED} \) can be formed using the known ambiguities and (46). Then (43)-(45) can be used for the \( \nabla \Delta \phi_k \) measurement of the new satellite.

5 Experimental results
The performance of the sensor fusion system is analized in real-time tests. The system was mounted on car as in Fig. 2.

5.1 Simple movement
During the first test the path of the car was chosen so that the performance of the system can easily be checked.
This simple path contains long straight lines where the heading direction and the velocity of the car is the same. The velocity is measured by GPS receiver, therefore a reliable reference is available. The path of the car can be seen in Fig. 4.

The measurement of the magnetic sensor can be seen in Fig. 5.

Using the output of the first extended Kalman filter the estimated heading direction can be calculated. The result is shown in Fig. 6.

The first stage gives basically the same result as the magnetometer. The only significant difference is
that the variance of the first stage result is more than two order smaller than the magnetic measurement.

Fig. 4. Path of the car during the simple movement

Fig. 5. Magnetic measurement during the simple movement

Fig. 6. Result of the first stage during the simple movement

The output of the first stage is compared to the reference heading direction. The result is that for the straight lines the heading error is smaller than 0.5°.

The result of the cycle slip detection is shown in Fig. 7.

Using the output of the cycle slip detection the second stage of the Kalman filters gave basically the same result as the first stage. This is because in this test the disturbance of the magnetic field was negligible.

One way to verify the reliability of the method is to examine the measured length of \( x_{r,s} \). As receiver r and s are fixed to the roof of the car, it is known that the real baseline length is 1.21 meters. The measured values are shown on Fig. 8.

Fig. 7. Output of the cycle slip detection during the simple movement

Fig. 8. The measured value of \( x_{r,s} \) during car movement

5.2 Complex motion

The second test is closer to the real applications. In this case the path of the car is more complex, the test is taken in an urban area. The disturbance of the magnetic field in this case is not negligible and there are points in the path, where the GPS is unavailable. On the other hand, the straight lines are kept, producing a heading reference in a similar way as in the first simple test. The path of car can be seen in Fig. 9.

Fig. 9. Path of the car in a complex motion

Fig. 10 presents the result of the state estimation during the complex motion.
Fig. 10. Heading direction during the complex motion

Analyzing the result, it can be said that the precision and the variance of the system is the same as in the simple test.

It can also be seen in Fig. 10 that there are plenty cases (20.5% of the whole time) where the GPS is unavailable (dead reckoning). In this case the orientation is the result of the first stage.

The advantage of the algorithms is that the integer ambiguity can be resolved using measurements from only one epoch. This means that the solutions can be initialized fast and are capable of switching back from dead reckoning to normal operation very quickly.

6 Conclusion

This paper presents a low-cost orientation estimation and sensor fusion system for outdoor vehicles. The system uses inertial, magnetic and GPS sensors. Carrier phase measurement capability is required for the GPS. Our system solves the integer ambiguity problem using the inertial and magnetic sensors. The orientation estimation has two phases. In the first one the angular velocity measurements are fused with the magnetic measurement performing an estimated orientation using an extended Kalman filter. This result is used by the second stage, where a more reliable orientation is produced using the GPS measurement.

The presented experimental results show the effectiveness of the developed methods. Important new research direction is the estimation of the angle of attack and the sideslip angle of aerial vehicles and their correction by the wind effect.

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