LIMITATIONS OF USE OF AN INERTIAL POSITIONING SYSTEM IN A TRUCK DURING A MANEUVER OF AVOIDING A SUDDENLY APPEARING OBSTACLE

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ABSTRACT

The objective of this work is to find limitations of using MEMS-type accelerometers and gyroscopes for finding position of a vehicle in short time prospective (few seconds). Such a system could be helpful for automated vehicle driving in some situations, like bypassing a suddenly appearing obstacle. A Monte-Carlo analysis was performed to find introduced position and direction errors for various trajectories of the vehicle. Transducer noise, offset and calibration errors were taken into account as possible error sources. Also, the influence of limited data sampling rate was checked. The results are presented in form of difference statistics between real and calculated vehicle position and orientation at the end of the track as function of various parameters, including the trajectory and performance of the used sensors. The Monte-Carlo simulation accuracy was checked by bootstrap method and the errors were shown in resulting plots. Presented results show that an inertial system can be used for determining the vehicle's position with accuracy reaching centimeters. Also, it is shown that compensation of the sensor offsets, as well as knowing the initial conditions are critical for the quality of the track reconstruction.

INTRODUCTION

For a suddenly appearing obstacle partly blocking the road, an attempt to bypass it can be a more efficient maneuver than braking, at least for certain velocities and track geometry [1,2]. This maneuver can be performed automatically if the vehicle is equipped with appropriate position sensors, like laser scanners, radars and cameras. However, such kind of sensors may be vulnerable to external disturbances like flashes of light, water splashes, fog, smoke or momentary electromagnetic interference. Also, their accuracy, sampling frequency and latency may not meet the requirements for rapid movements. This makes a need to provide a system which is free of aforementioned drawbacks. It should provide vehicle position data in a time period of few seconds needed for maneuver completion, with good-enough accuracy, immunity to external interference and low latency. Modern MEMS-type inertial sensors (linear accelerometers and gyroscopes, i.e. angular speed sensors) seem to be a good candidate to be used for this purpose.
The aim of this work is to find limitations of use of these sensors due to their noise, miscalibration and generally ill-conditioned integration-based method of vehicle position reconstruction. To achieve this goal, a number of Monte-Carlo simulations were performed for different conditions, including noise of the sensors, sampling frequency, miscalibration, track geometry, initial vehicle velocity and deceleration during the maneuver.

MARKET-AVAILABLE SENSORS

The manufacturers offer a variety of MEMS-based sensors for acceleration and angular velocity. Their performance is closely related to their intended application and related customer's budget, ranging from simple orientation sensors used for mobile phones, through sensors for game-console controllers, up to professional sensors which can be used in so demanding applications as autonomous control of drones or even 'big' aviation. Several sensors (including high-performance devices) are listed in Table 1. One of them – namely LSM330DL – contains both accelerometer and gyroscope in a single chip. Its parameters were used as base values for a number of performed simulations.
At this point, it's worth noting that also chip-integrated magnetometers are available which can provide absolute information on vehicle orientation, however their use for our purpose is generally pointless. This is due to their non-

negligible latency, relatively low sampling rate and – last but not least – vulnerability to interference from external sources of magnetic fields.

Table1.
Several types of MEMS accelerometers and gyroscopes and their main parameters.

Type	Accelerometer			Gyroscope		
	Range [m/s^2]	Noise density $\left[\frac{m/s^2}{\sqrt{Hz}}\right]$	Sample rate [Hz]	Range [^{o}/s]	Noise density $\left[\frac{^o/s}{\sqrt{Hz}}\right]$	Sample rate [Hz]
LIS3DH [1]	20-160	$2.2\cdot10^{-3}$	5000	*n/a*	*n/a*	*n/a*
LIS33DE	20-80	*not specified*	400	*n/a*	*n/a*	*n/a*
LSM330DL [2]	20-160	$2.2\cdot10^{-3}$	5000	250-2000	$3.0\cdot10^{-2}$	1344
L3G4200D [3]	*n/a*	*n/a*	*n/a*	250-2000	$3.0\cdot10^{-2}$	800
CMR3000-D01	*n/a*	*n/a*	*n/a*	2000	$2.0\cdot10^{-1}$	160

MONTE CARLO SIMULATION PROCESS

The basic simulation process consisted of few steps:

- calculating the position of the vehicle along a defined track over time with dense time step (typ. 1 ms);
- calculating the data for sensors, i.e. the values of acceleration (tangential and normal component related to the vehicle trajectory) and angular velocity over the vertical axis;
- decimating the above data to get undisturbed sensor data at real sampling frequency of the sensor;
- disturbing the data to get simulated data of a real sensor;
- track reconstruction basing on disturbed data;
- finding the reconstruction errors.

Last three steps were performed multiple times (typically 1000) to get statistical information on errors. Basing on acquired data, the mean value of the error, its standard deviation and RMS (root-mean-square) value were calculated.
The whole procedure was performed for various conditions, e.g. varying noise of the sensors, vehicle speed or track length. Following further assumptions were made in order to perform the simulations:

The shape of the track

It is assumed that the vehicle moves along a straight road with a constant velocity as the maneuver begins. Then it changes its position across the road by a certain displacement (denoted as D) while moving forward. The total distance along the road during this movement (denoted as L) is generally longer than D. The track has a shape of half-cosine, according to Equation 1:

$$d(l) = \frac{1}{2} D \cdot \left(1 - \cos\frac{\pi \cdot l}{L}\right) \tag{1}$$

where l and d denote actual vehicle position along and across the road, respectively. One must note that l can not be treated as linearly changing with time, as the velocity of the vehicle is calculated along its trajectory and not along the road.
For the purpose of simulation, two short segments of straight track (parallel to the road) are added at the beginning and the end of the track. Their length is determined according to the vehicle's velocity so that their duration is about 100 ms. The aim of inserting these segments is purely technical – an amount of data is to be generated to feed digital filters for data decimation, so that no oscillations at the beginning and the end of the track occur.

It's obvious that discontinuities in acceleration and angular velocity are present at the beginning and the end of the proposed half-cosine track. Despite that such kind of track is impossible to be followed in reality, these discontinuities are not an obstacle for the track reconstruction algorithm. Thus, the assumed model of the track is acceptable for our purpose.
Last but not least, it must be noted that our model is two-dimensional. This means that possible vehicle tilting is not taken into account. The consequence of this assumption is that only two acceleration sensors among three (one for each axis) are used in the track reconstruction procedure – a sensor for vertical acceleration is not used. Accordingly, only one rotation sensor is used – this is the one to measure angular speed over the vertical axis.

Sensor models

The sensors are outputting data with a defined sample rate. It's assumed that the data acquisition time is zero (i.e. the value of the sample refers to a certain moment and is not an effect of averaging of the input value over a period of time).
It was assumed that the sensors have following errors:

- Sensor noise, which is stationary, white in spectrum and has Gaussian probability density function (PDF). During simulation, a random value of noise is added to each sample of the sensor data. The input data for the simulation is the power spectral density of the noise, which is re-calculated to variance of a single sample.
- Sensor miscalibration, which has also Gaussian PDF. Sensor miscalibration is a constant value added to the sensor data for the whole realization, i.e. single MC attempt. However, it's determined independently for each realization, giving a spectrum of different results after a number of MC loops.

Track reconstruction algorithm

The aim of this algorithm is to calculate vehicle position and orientation (the angle between the vehicle's axis and initial movement direction) basing on the sensor data. The calculation is performed with a defined timestamp, which is identical with sampling period of the sensors. Actually, two main activities are performed for each time point: calculation of the vehicle orientation (i.e. the angle between the axis of the vehicle and the axis of the road) and position.
The vehicle orientation calculation is performed using only the data from the angular velocity sensor. For a given time point t_n, the vehicle's orientation ψ is calculated as:

$$\psi(t_n) = \psi(t_{n-1}) + T_s \cdot \Omega(t_n) \tag{2}$$

where $\psi\ (t_{n-1})$ denotes vehicle orientation for the previous time point, $\Omega(t_n)$ the measured angular velocity and T_s the sampling period.
The position reconstruction requires three consecutive steps: acceleration measurement, velocity calculation and position calculation.
For the first step, the sensor data is re-calculated from vehicle coordinates to road-related *l-d* coordinates, as it's presented in Equation 3:

$$\begin{aligned} a_l &= a_{par} \cdot \cos\psi - a_{perp} \cdot \sin\psi \\ a_d &= a_{par} \cdot \sin\psi + a_{perp} \cdot \cos\psi \end{aligned} \tag{3}$$

where a_{par} and a_{perp} are acceleration values measured with respect to the vehicle's axis (parallel and perpendicular, respectively) and ψ is the calculated current vehicle orientation. The a_l and a_d denote the acceleration values in along *l* and *d* axis.
The velocity is calculated by integrating the acceleration values, basically the same way as it was done for vehicle orientation. Then, one more integration step is performed to get the position values.

Dependencies to check

The influence of the following factors on the achievable accuracy was checked:

- noise spectral density of the accelerometers and gyroscopes,
- miscalibration of the sensors (constant offset of the sensor readout),
- limited sampling rate of the sensors,
- length of the track along initial movement direction,
- initial vehicle velocity,
- vehicle deceleration during the maneuver.

Witch such a number of variables, performing simulations for all parameter combinations was virtually impossible. Thus, only 2-dimensional maps were calculated (i.e. the dependence on two selected parameters) with remaining parameters fixed at a constant value.

The basic parameter set was as follows:

- track length (L): 50 m (20 m for sample rate tests),
- track width (D): 5 m,
- initial velocity: 20 m/s
- vehicle deceleration: 0 m/s^2
- sample rate of the sensors: 100 Hz
- spectral noise density of the accelerometer: $2.2 \cdot 10^{-3}$ $m/s^2/\sqrt{Hz}$,
- spectral noise density of the gyroscope: $3.0 \cdot 10^{-2}$ $^o/s/\sqrt{Hz}$,
- accelerometer miscalibration: 0 m/s^2,
- gyroscope miscalibration: 0 $^o/s$.

Error calculation

The errors are present in each sample of the reconstructed data. However, they generally grow with time due to integration-based method of the track reconstruction – the error of any data sample is a result of the error of previous sample and new errors introduced by the sensors. Thus, the errors at the end of the track are statistically the biggest ones. For this reason, we used these 'final' errors as a gauge of the reconstruction quality.

Following errors were checked:

- misalignment in vehicle position at the end of the simulation, calculated independently in *d* and *l* axis, as well as combined position error;
- vehicle orientation error;
- the error of final movement direction.

The vehicle orientation and movement direction must be distinguished, as it is not an assumption that the vehicle is always moving along its axis. Even if we neglect small differences due to vehicle's chassis geometry, also huge discrepancies may occur if the vehicle gets into a skid. The reconstruction algorithm must take such a situation into account.

Basing on MC simulations, error statistics were gathered, giving following values:

- Error mean value. Generally, for 'input' errors with zero mean value, the mean value of the 'output' error should be also zero for a linear model. However, as our model is not linear, non-zero values may occur. It this controversial if this error can be suppressed in practice (despite it's theoretically deterministic), as its value may be strongly dependent on track parameters. Thus, we treat this error as incorrectable.
- Standard deviation of the error values. Only error spread is taken into account and not its mean value.
- Root Mean Square (RMS) value of an error. Both above components are incorporated in this value. It was used as a basic gauge during simulations.

BASIC RESULTS

In the following sections, basic results were presented in form of plots showing error RMS value as a function of various factors. Typically, each plot presents a family of curves showing the error dependence on two parameters. For each plot, 3σ error bars are plotted to show Monte-Carlo simulation accuracy.

Influence of the sensor noise

Figure 1 presents a set of plots showing the dependence of the errors on the noise of the sensors. Upper plots show the position reconstruction accuracy in two axes. Lower plots show movement direction error (left) and vehicle orientation error (right).

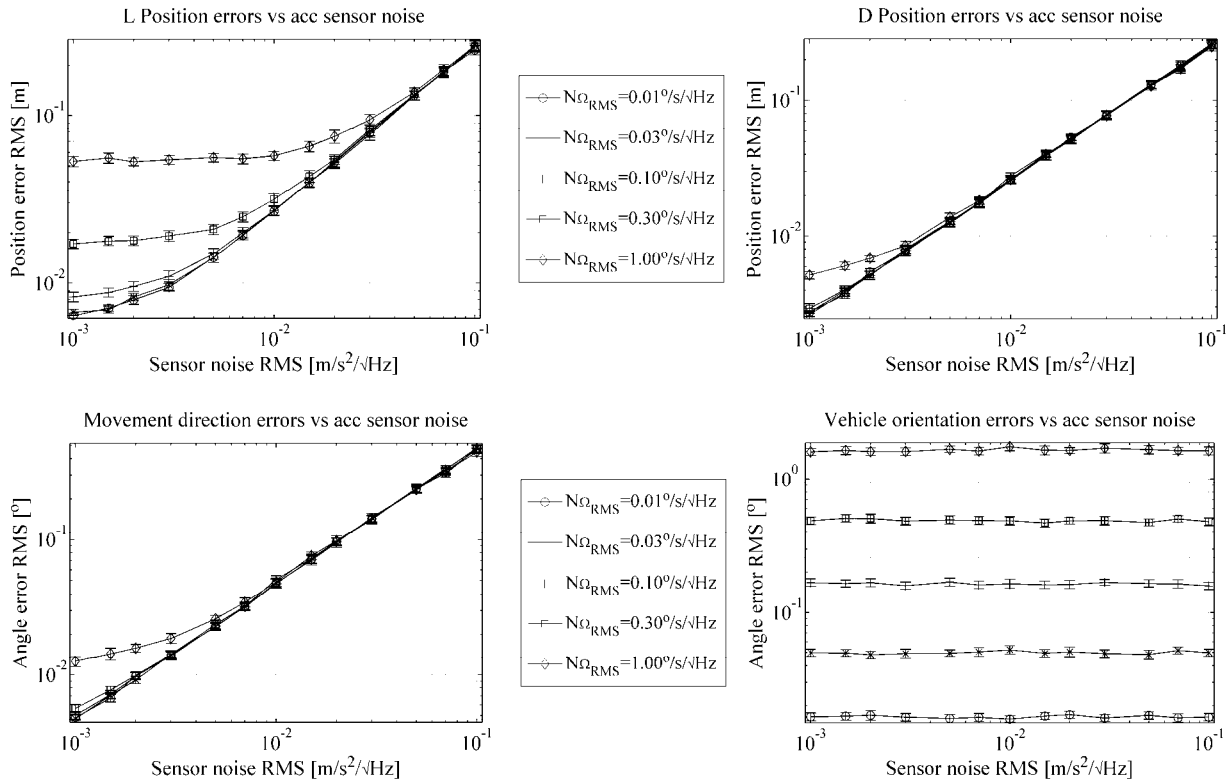

Figure 1. The influence of the sensor noise on the track reconstruction. Upper plots present position reconstruction error, while lower ones show angle reconstruction errors.

At this point, it should be noted that:

- For a given track geometry, the position reconstruction error is dependent mainly on the noise of the acceleration sensor. The influence of the gyroscope noise is visible mainly for the longitudinal component and only for high noise levels.
- The vehicle orientation reconstruction accuracy is dependent only on the noise of the angular velocity sensor, which is obvious given the reconstruction method described previously (see Equation 2).
- The accuracy of movement direction reconstruction is dependent mainly on the noise of the angular velocity sensor, but also an influence of the accelerometers can be observed for high noise amplitude.

Generally, the error values are small for expected noise levels of real sensors. For LSM330DL, the total position error should be below 1 cm for given track geometry and vehicle velocity of 20 m/s. Also, the vehicle orientation and movement direction accuracy should be well within 1°, which is more than satisfactory. Of course, these promising results should not be treated too seriously before analyzing the influence of track geometry, initial speed, sensor miscalibration etc.

Influence of the sensor miscalibration

Generally, the influence of sensor miscalibration is close (in its character) to the one of sensor noise, as Figure 2 shows. The main difference in the character of the curves is that no influence of miscalibration of the angular velocity sensor on position accuracy was observed.
If we define maximum errors as 0.1 m and 1° RMS, the allowable miscalibration values for given default conditions (see *Simulation Process, Dependencies to check*) are $3 \cdot 10^{-2}$ m/s^2 and $3 \cdot 10^{-1}$ ^{o}/s. One can see that assuring good sensor offset compensation is critical. Thus, an on-line algorithm is required to compensate slowly varying offsets of the sensors.

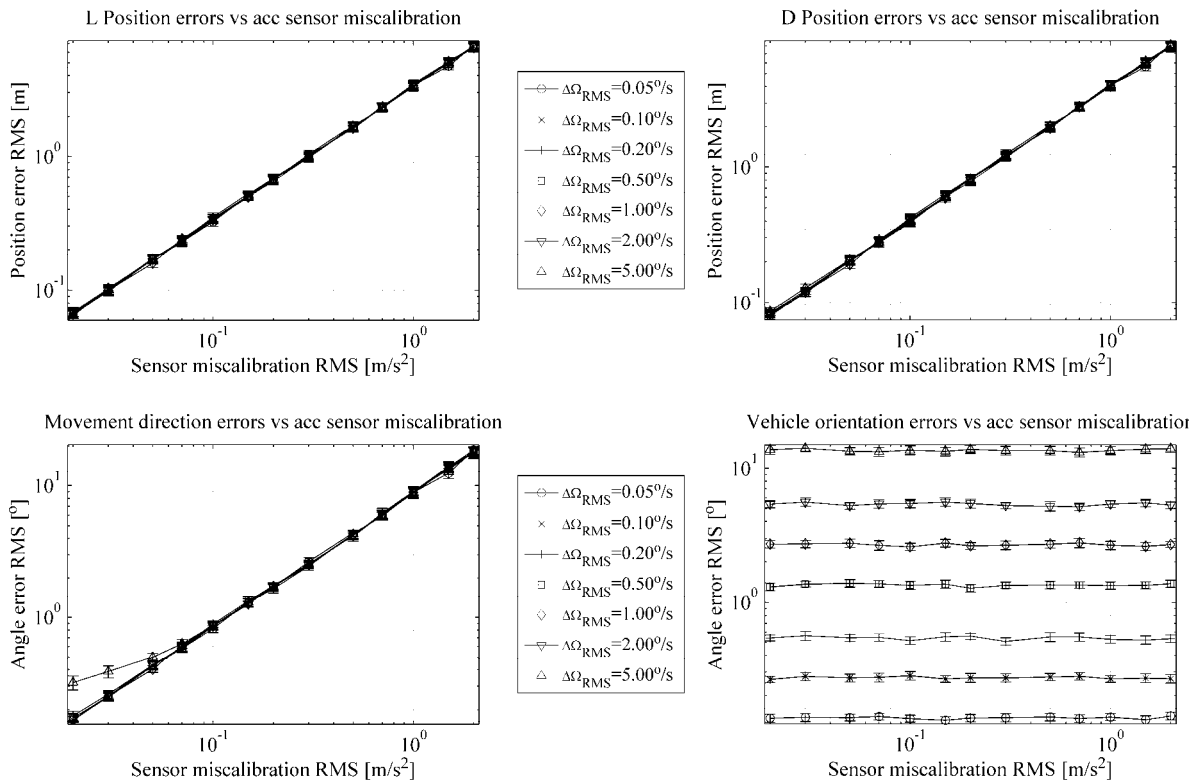

Figure 2. The influence of the sensor miscalibration on the track reconstruction.

Influence of uncertainties in initial conditions

The next possible error source is the uncertainty in initial conditions, i.e. vehicle velocity and movement direction. According to Figure 3, the simulations have shown that:

- The position reconstruction accuracy is dependent on errors both in initial velocity and movement direction. However, the influence of both parameters is different for longitudinal and perpendicular component of the displacement. As for the errors along the road, both error sources are sigificant. However, the influence on position across the road is dominated by initial direction errors.
- The accuracy of reconstruction of final movement direction and vehicle orientation is dependent only on initial direction error (it was checked that the influence of errors in initial velocity can be seen only for huge errors, which are comparable with the real value of the initial velocity).
- Achieving tolerable errors (0.1m / 1°) require that the initial velocity error is lower than ≈0.02 m/s and the initial movement direction is defined with an accuracy of 0.1^o. These requirements are very demanding, especially for the velocity measurement. However, one can see that mainly the longitudinal position is vulnerable to initial velocity (see Figure 3, upper left plot). Thus if we decrease our requirements for this

axis (it's less critical than the perpendicular component of the position), also the requirements on initial velocity requirement will become less tight.

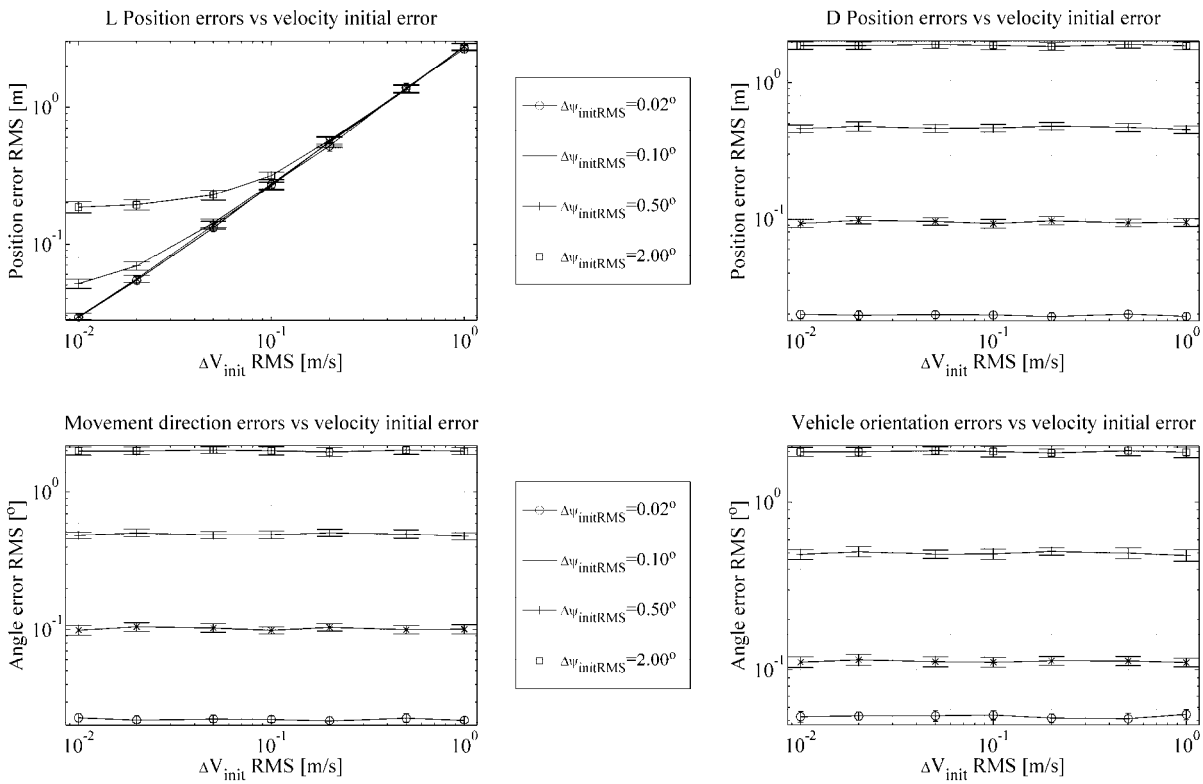

Figure 3. The influence of errors in initial velocity and angle measurement on the track reconstruction.

Influence of varying trajectory, vehicle velocity and deceleration

All presented results were obtained with a fixed track geometry (i.e. its length *L* and width *D*) and constant speed of 20 m/s. The question is, how these results change with the length of the track, initial speed and possible deceleration during the manoeuver.

For following simulations, all possible error sources were included. The simulation parameters were as follows:

- Spectral noise density of the accelerometers: $2.2\cdot10^{-3}\ \mathrm{m/s^2}/\sqrt{\mathrm{Hz}}$,
- Spectral noise density of the angular velocity sensor: $3.0\cdot10^{-3}\ {}^{\circ}\mathrm{/s}/\sqrt{\mathrm{Hz}}$,
- Miscalibration of the accelerometers: 0.01 $\mathrm{m/s^2}$ RMS
- Miscalibration of the angular velocity sensor: 0.1 °/s RMS
- Error in initial velocity: 0.01 m/s RMS
- Error in initial vehicle orienttion: 0.1 ° RMS
- Sampling frequency of the sensors: 100 Hz

The distance along the road for deceleration-dependent plots was 50 m.

The results are presented in Figure 4. One can see that a combination of all disturbing factors may cause position errors exceeding 1m, especially for long distances and small vehicle velocity. Mostly sensor miscalibration and errors in initial conditions are responsible for this value. It was checked, that the accuracy in both axes is influenced. The distinctive peaks on the deceleration-related plots (right side of Figure 4) are related to a situation where the deceleration causes the vehicle to stop at the end of the maneuver.

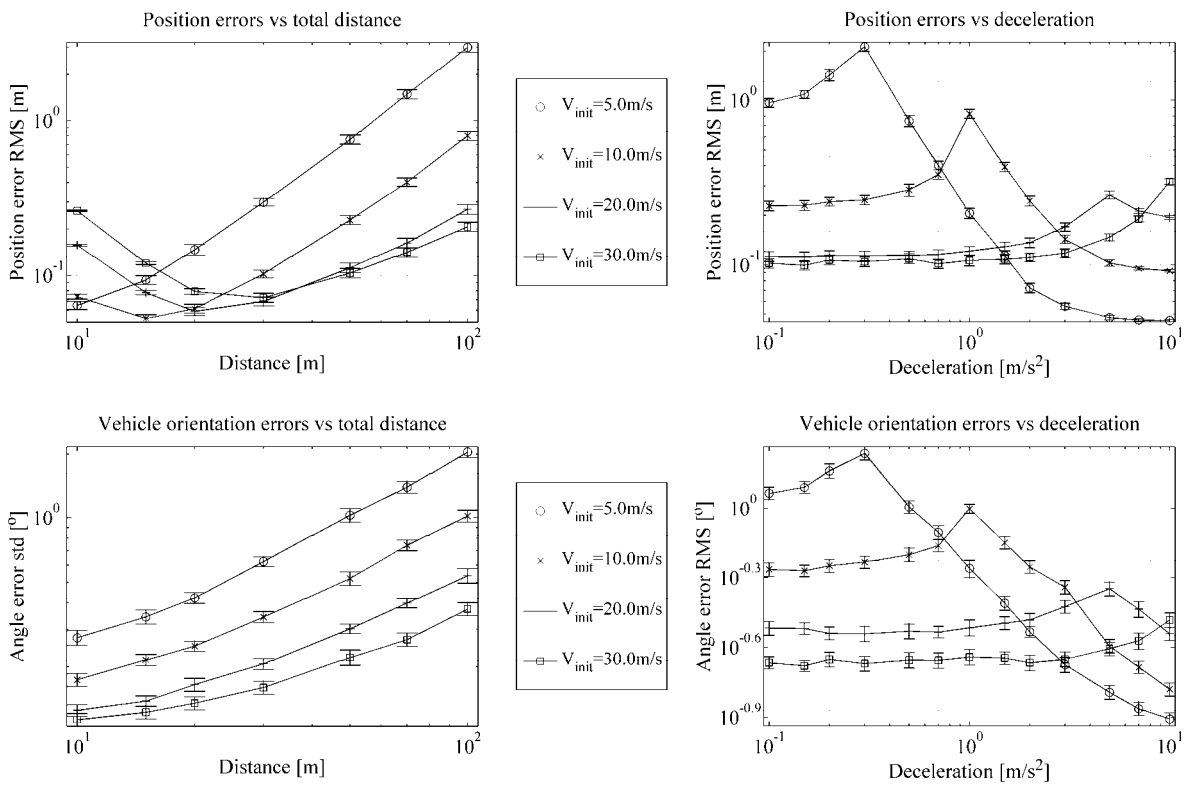

Figure 4. The influence of the track geometry, initial velocity and deceleration on the track reconstruction.

Influence of the sampling rate

The last simulation was performed to check the influence of the sampling rate of the converters on the results (Figure 5). The general outcome is that:

- the sampling frequency is more important for high velocities and narrow track shapes;
- for typical conditions, the sampling frequency in range of 100-400 Hz is sufficient.

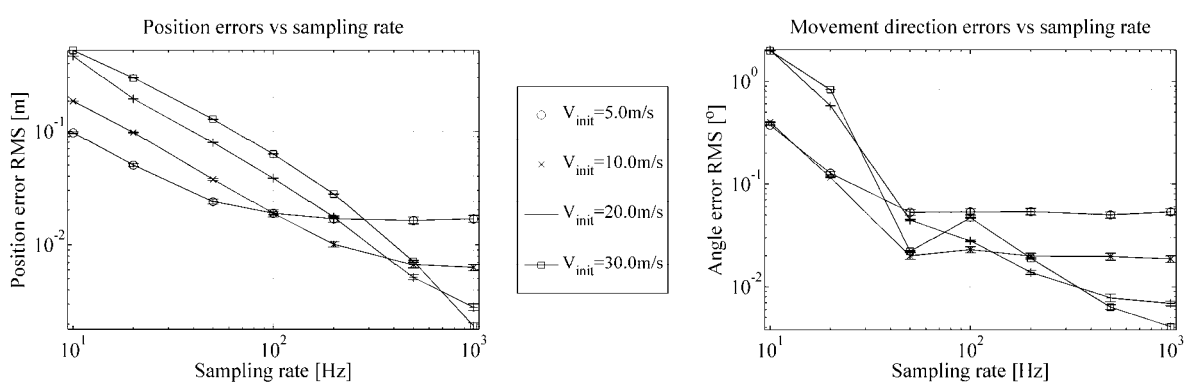

Figure 5. The influence of the sampling rate of the converters on the track reconstruction. Track length along the road is 20 m.

CONCLUSIONS AND DISCUSSION

The presented research included an analysis of achievable accuracy of a system of inertial sensors intended for automated driving of a vehicle. The results show that driving a vehicle using only inertial sensors (accelerometers and gyroscopes) is possible over short distances reaching few dozens of meters.
The crucial factors determining the accuracy of position reconstruction are good calibration of the sensors, proper offset compensation and undisturbed information on initial conditions (vehicle's velocity vector and position). It was checked that the noise of the sensors is not a foreground component determining the accuracy. The requirements regarding the noise are easy to fulfill using modern MEMS-type sensors.
The simulations have shown that lowest errors are achievable for short times, i.e. for short track lengths and high velocities. However, some issues concerning the sample rate of the sensors may influence the accuracy for very rapid movements. Proper data interpolation may partly compensate this effect, but it will never be fully eliminated.

One must take into account the limitations of the simulations. First, all of them were performed using the same track shape – half-sine. Second, the used model is only two-dimensional, while vehicle tilting may require 3-dimensional reconstruction in real applications.
The aforementioned restrictions are not an effect of limited capabilities of the developed simulation engine. They were introduced intentionally to reduce the number of possible combinations of factors influencing the results. We believe that, for such a generic research, clear representation of the results is more important that covering the full area of possible input parameters. The obtained results should be representative and easily extendable over different track geometries and switching to a 3-dimensional model should cause only moderate accuracy degradation.

The tests reported herein were carried out and their results were analysed within an authors' own research project No. N N509 568439.

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