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Analyse of MEMS Based Inertial Sensors Parameters for Land Vehicle Navigation Application

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Abstract: The last decade has shown an increasing demand for small-sized and low-cost inertial navigation system for use in many applications such as vehicle navigation, personal navigation.

This study has emphasized the error characterization and performance analysis of MEMS based 3-axis accelerometer trying to turn the raw measurements of the sensors into reliable and useful for further vehicle position and velocity determination. The 3-axis accelerometer was tested in static mode in order to obtain information about its bias and scale factor and in dynamic mode in order to check its performance for land vehicle velocity and passed distance estimation. Experiments showed that inherent errors of MEMS based 3-axis accelerometer have a big impact on estimated velocity and distance. The estimated vehicle velocity and distance have no considerable noise fluctuations, due to the integration operation used for it calculating.

Key words: MEMS, IMU, land vehicle, acceleration, velocity, distance

Introduction

Land vehicle navigation system technology is a subject of great interest today due to its potential for both consumer and business vehicle markets.

GPS measurements are the essential information for land vehicle navigation systems. However, GPS alone is incapable of providing continuous and reliable navigation solutions, because of its inherent dependency on external electromagnetic signals.

In order to overcome the unavailability or unreliability problem in satellite based navigation systems and also to be cost effective, Micro Electro Mechanical Systems (MEMS) based inertial sensor technology creates opportunity to have low-cost integrated navigation systems. MEM is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of microfabrication technology [1, 2].

Since the usage of high performance inertial navigation systems (INSs) is limited by their high price and the regulation by the government, therefore low cost INSs are used for land vehicle navigation.. However, low cost INSs can experience large positioning errors in very short time due to the low quality of the inertial measuring unit (IMU). MEMS based accelerometers and gyroscopes are becoming more attractive to manufacturers of navigation systems because of their small size, low cost, light weight, low power consumption and ruggedness [1, 3].

The equipment used for research in the present paper is a MEMS-based Motion Node IMU from GLI Interactive LLC. This IMU consists of 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer.

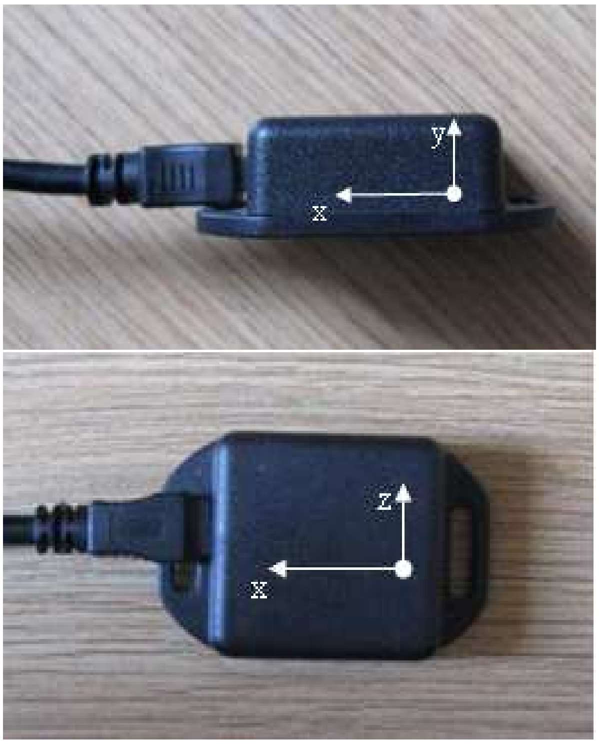

Fig. 1 Inertial measurement unit Motion Node and sensor reference frame

The fundamental characteristics (errors) of MEMS based accelerometers will be investigated in this paper. For MEMS based inertial sensors, their deterministic error sources are mainly focused on zero-offset bias and 1st scale factor. The errors in the observations from the MEMS-based sensors must be appropriately treated in order to turn the observations into useful data for vehicle position determination.

Also tests with IMU Motion Node will be conducted in order to estimate acceleration, velocity of land vehicle and distance passed by it.

IMU bias and scale factor determination

The output signal of accelerometer can be expressed approximately in terms of an applied acceleration and the sensor error coefficients as follows [1]:

$$acc_{out}=(1+SF)\cdot a+bias+noise, \qquad (1)$$

where acc_{out}- measurement provided by an accelerometer, SF- scale factor of accelerometer, bias- bias of accelerometer, noise- random bias or random component of measurement.

In order to estimate bias and scale factor of accelerometer the following measurement procedure is performed during experiment. The procedure is to let each axis of measurement idle while sensing the gravity vector along the local vertical upwards and then downwards. The biases affecting the measurements are estimated according to the following equations:

$$\begin{aligned} acc_{out1}&=(1+SF)\cdot g+bias \\ acc_{out2}&=-(1+SF)\cdot g+bias, \end{aligned} \qquad (2)$$

where acc_{out1}, acc_{out2} – accelerometer measurements, when local vertical upwards and downwards, g- the acceleration of gravity.

$$bias=(E\{acc_{out1}\}-E\{acc_{out2}\})/2, \qquad (3)$$

where $E\,\{.\}$- expectation operator.

In order to eliminate measurement noise impact on bias and scale factor calculation 5- one minute long measurements are made and then results of measurement are averaged. The rate of measurement is 60 samples per second. It's well-known that characteristics of accelerometer change with time. Therefore repeated tests conducted after one and two days to see the difference of estimated bias values. Results of these tests are shown in Fig.2.

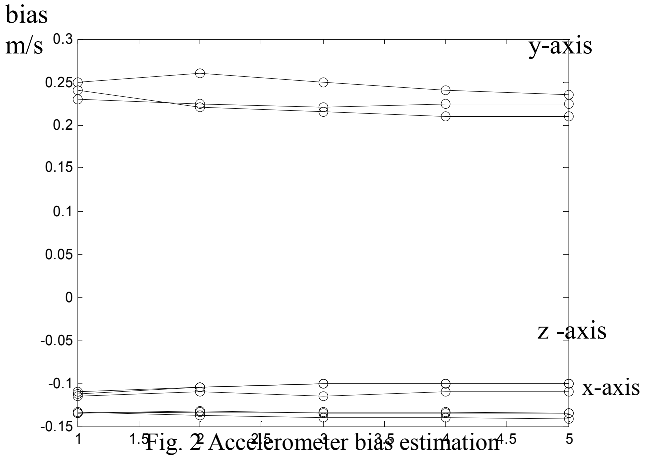

Fig. 2 Accelerometer bias estimation

The expression for accelerometer scale factor can be also found using equations (2):

$$SF=(E\{acc_{out1}\}-E\{acc_{out2}\}-2\cdot g)/2\cdot g, \qquad (4)$$

where g-the acceleration of gravity.

International Gravity Formula is used for the acceleration of gravity (g=9.8148 m/s^2) calculation:

$$g(\varphi)=9.780327\cdot(1+0.0053024\cdot\sin^2\varphi-0.0000058\cdot\sin^2\varphi)-3.086\cdot10^{-6}h \qquad (5)$$

where φ-latitude, h- height in meters above sea level. The results of accelerometer bias and scale factor estimation are shown in Table 1.

Table 1. Bias and scale factor of 3-axis accelerometer

	X-axis	
	bias,m/s^2	**SF**
mean	-0.1418	-0.0043
deviation	0.0014	9.6177e-005
	Y-axis	
mean	0.2275	-0.00079
deviation	0.0023	4.9800e-004
	Z-axis	
mean	-0.1060	-0.0019
deviation	0.0020	1.6733e-004

The values of bias and scale factor from Table 1 prove that Motion Node have low-quality class accelerometers according classification in [3].

Kinematic tests setup with IMU Motion Node

Kinematic tests are made in order to obtain acceleration data of vehicle, so then to calculate its velocity and passed distance.

Tests are conducted on the straight road (see Fig.3).

Fig.3 Route taken for experiments

IMU Motion Node was fixed rigidly on a board inside vehicle in order the sensor reference frame (Fig. 1) coincided with vehicle reference frame (Fig.4). The IMU is connected to notebook via USB interface during experiments. Output accelerometer data is recorded at 60Hz to the notebook for it further postprocessing in Matlab. Data collection for each test began with IMU static initialization period of about 15 minutes.

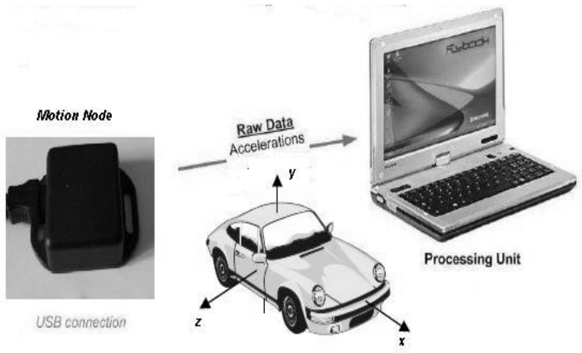

Fig. 4 Kinematic testing system

There're three stages of the vehicle movement during experiment: acceleration till the defined value of velocity, almost uniform movement with defined velocity and breaking. Three values of velocity have been chosen for tests: 40 km/h, 60 km/h, 75 km/h. The data of vehicle speedometer, odometer is used as indication of its velocity and passed distance.

It's necessary to make integration of sensor acceleration data in order to obtain values of vechicle's velocity and passed distance:

$$\begin{aligned} v(T) &= \int_0^T a(t)dt + v(0); \\ s(T) &= \int_0^T v(t)dt + s(0); \end{aligned} \tag{6}$$

where v –vechicle velocity, s- passed distance, $s(0)$ and $v(0)$ velocity and distance initial values.

Acceleration data from sensor output was corrected for errors (bias) and then numerical integration of acceleration data (Fig. 5, 8,11) was performed in order to calculate vehicle velocity and distance curves. The results of experiments are shown in the Fig.5-13.

Kinematic test, when vehicle velocity is 40km/h and passed distance is 750m.

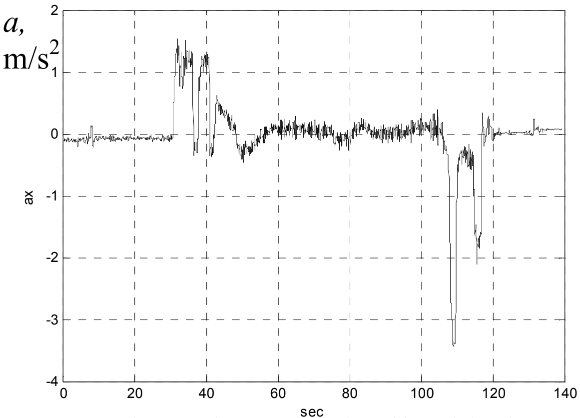

Fig.5 Accelerometer (x-axis) calibrated signals

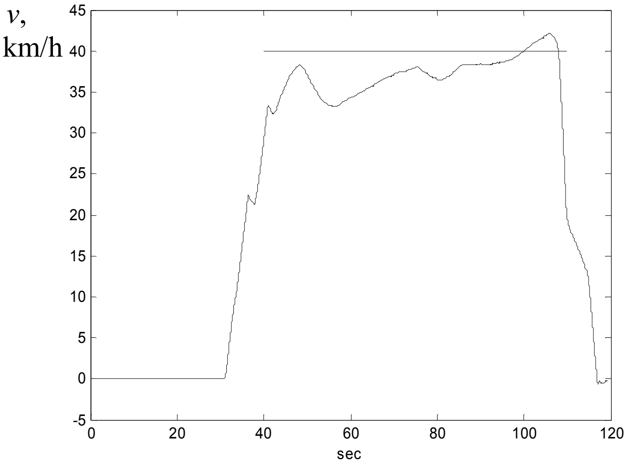

Fig.6 Vehicle velocity estimation

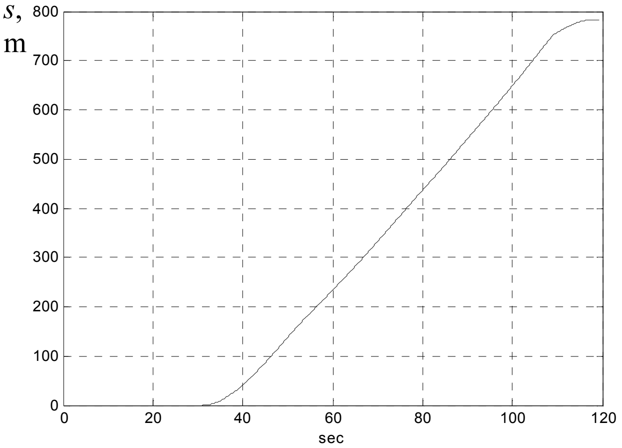

Fig. 7 The passed distance estimation (s=780m)

Kinematic test, when vehicle velocity is 60km/h and passed distance is 1050m.

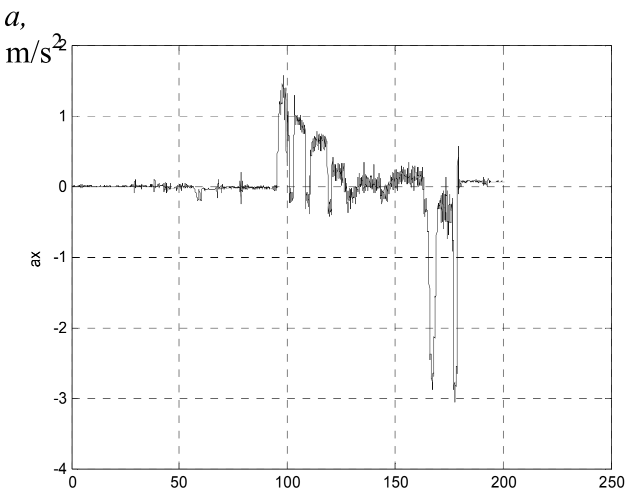

Fig.8 Accelerometer (x-axis) calibrated signals

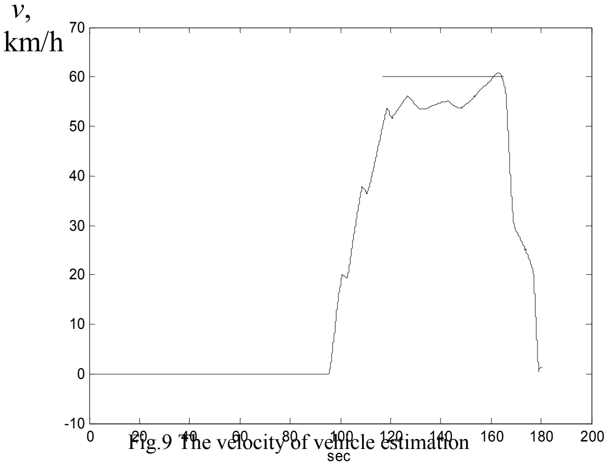

Fig.9 The velocity of vehicle estimation

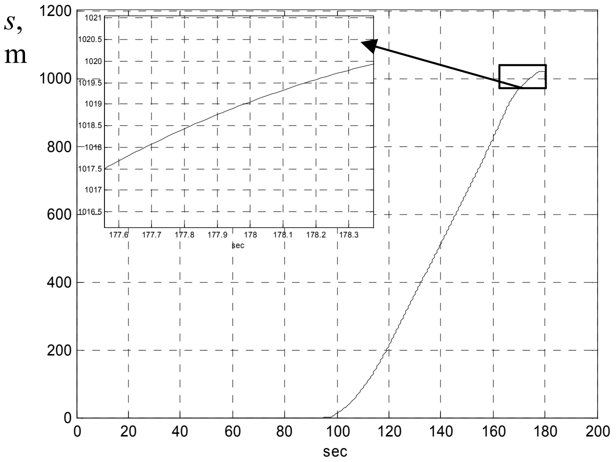

Fig. 10 The passed distance estimation (*s*=1020m)

Kinematic test, when vehicle velocity is 75km/h and passed distance is 1100m.

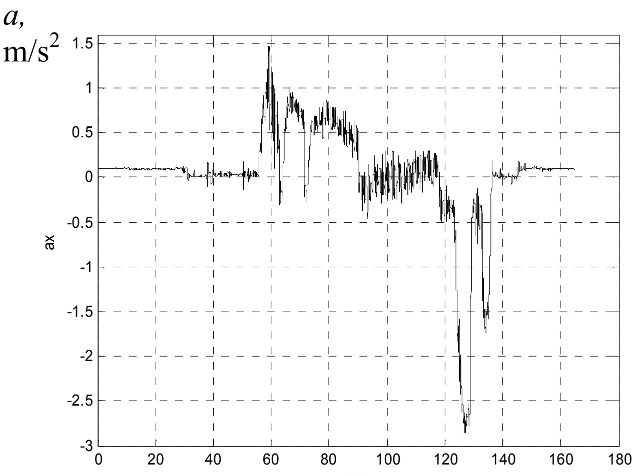

Fig.11 Accelerometer (x-axis) calibrated signals

The level of noise fluctuations of estimated parameters –velocity and distance - are shown by zooming fragments of corresponding curves in Fig.12, 13.

It can be noticed that level of noise fluctuations decrease comparing Fig. 11 with Fig.12 and Fig.13, so that acceleration data (Fig.11) is the most noisy.

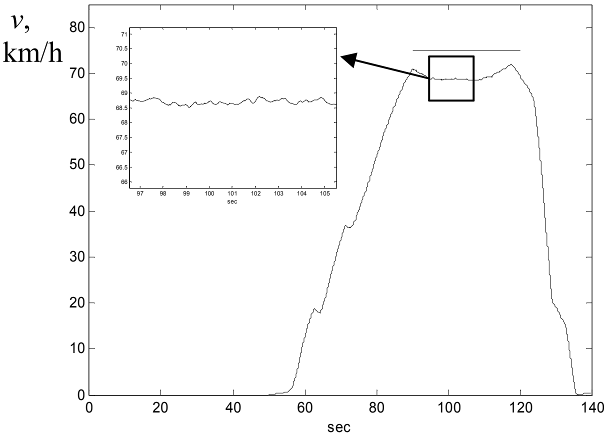

Fig.12 The velocity of vehicle estimation

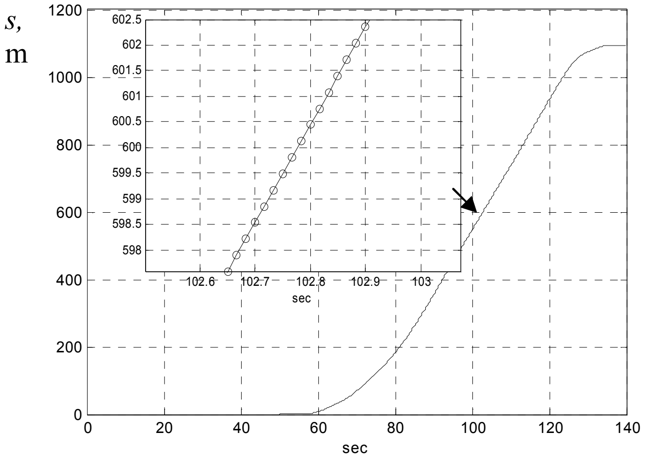

Fig.13 The passed distance estimation (*s*=1090m) and zoomed fragment near distance value of 600 m

The estimated values of the passed distance are very near to the odometer indication (Fig. 7, 10, 13). It can be noticed from zoomed fragment of Fig.13 that calculated function of distance is linear (the quantity of the calculated distance values is 60 per second). There are no noise fluctuations of the estimated values. This is due to the integration operations, which are used for distance estimation according equation set (6). Lack of noise fluctuations of the estimated values can be considered as an advantage for IMU based navigation system.

Some non linear velocity changes can be found on calculated curves on Fig. 6, 9, 12. Nonlinearity of function during vehicle uniform movement can be explained by difficulty of vehicle velocity maintaining at nearly constant level during tests.

Extra tests with video camera prove that calculated functional changes of velocity correspond precisely to vehicle dynamic characteristics and its change during experiments. For example, there’re three zones indicated by circles on the curves in the Fig. 14. These zones correspond to the moments of vehicle gear shifting. In fact there’s always small velocity decreasing before gear shifting and after velocity increases again.

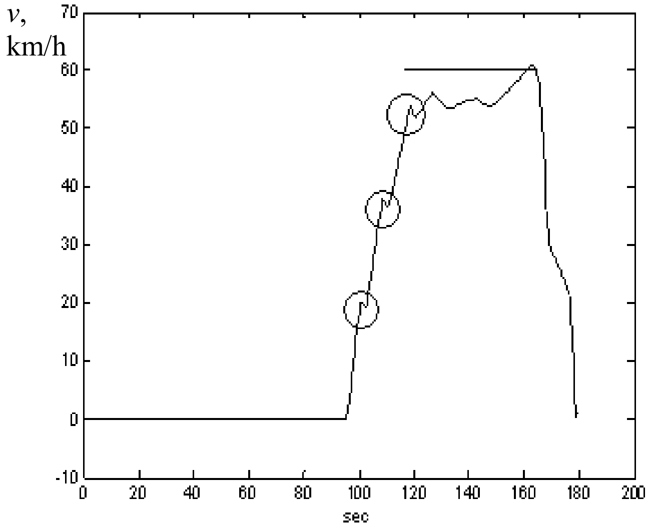

Fig.14 Vehicle velocity estimation

Conclusions

The main objectives of this paper are to investigate the error behaviors of MEMS based inertial sensors and to make the performance analysis of a low-cost MEMS based 3-axis accelerometer for land vehicle navigation in case of its straight line movement. The major motivation is that GPS signal is not always available to the users and GPS based solutions are degraded due to poor geometry, and multipath effect even though GPS based navigation system is becoming smaller and inexpensive, and nowadays is more popular and attainable for civil users [1,2].

The tests were conducted with IMU Motion Node in static mode for accelerometer error parameter estimation. Also experiments were made with IMU in dynamic mode, when IMU was placed inside the moving test vehicle.

The test results in static mode show that IMU parameters quality is low and IMU can not be used for land vehicle navigation without appropriate error compensation. Therefore it is strictly recommended to identify the various deterministic error sources of the sensors and quantify them for optimal data processing algorithm and performance analysis.

The results of experiments for the vehicle velocity and passed distance estimation were satisfactory for short period of time. The indication of vehicle odometer and speedometer was near to estimated values based on accelerometer output data. The estimated values have no considerable noise fluctuations, due to the integration operation used for it calculating.

More precise reference navigation systems are required for to make more precise analyse of the velocity and distance estimation error of IMU Motion Node based navigation system. These can be GPS receiver or higher class IMU based navigation system. This analyze allow to built MEMS IMU error model that allow to eliminate distance estimation errors more efficiently.

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