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DEVELOPMENT AND FIELD TESTING OF A MICROMACHINED INERTIAL SATELLITE SYSTEM FOR ROAD DEPARTURE WARNING INTENDED FOR PASSENGER VEHICLES

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Abstract

The report presents a road departure warning system intended for passenger vehicles, results of its laboratory calibration and field testing. The system consists of a micromachined inertial measurement unit CROSSBOW, a GPS receiver, two odometers, and a processor which implements a navigation algorithm and a Kalman filter. It has been proved experimentally that the software and hardware developed ensure the accuracy sufficient for passenger vehicle safety systems and provide the RMS error of the vehicle’s relative coordinate determination by the system no greater than (20–30) cm after 5 sec of the GPS silence and at the vehicle’s speed up to 30 mps.

Introduction

Every year over a million people die in road crashes around the world, and over 10 million are crippled or injured. In the US one dies every 13 minutes in a motor vehicle crash. The study forecast that by the year 2020 road crashes would move up to third place in the table of causes of death and disability. Cost of traffic crashes only in US for the year 1994 was around $150.5 billion.

Run-off-road crashes are most frequent among all vehicle fatalities. A U.S. statistical review indicates that those occupy over 41% in the crash population. Driver errors are a cause for about 93 percent of the crashes [1]. At least 30% of these crashes may be avoided if information is provided to the driver about the possible emergency by a so-called Road Departure Warning System (RDWS). According to US Transportation National Highway Traffic Administration study, RDWS has potential to save $6.4 billion dollars each year.

The key issues of RDWS development are: (1) highly accurate and robust measurement of the vehicle's position with respect to the road in real time; (2) prediction and identification of an emergency in real time; (3) creation and timely maintenance of a detailed road information database; (4) reduction of the price of an RDWS set below $500.

This report deals with issues of accuracy of the principal RDWS subsystem — the system for positioning the vehicle with respect to the road (a vehicle road positioning system). The main attention will be paid to the error of the relative coordinate determination when GPS satellites are temporarily silent (not intercepted).

Description of the system

The basic structure of the system is presented in Fig.1

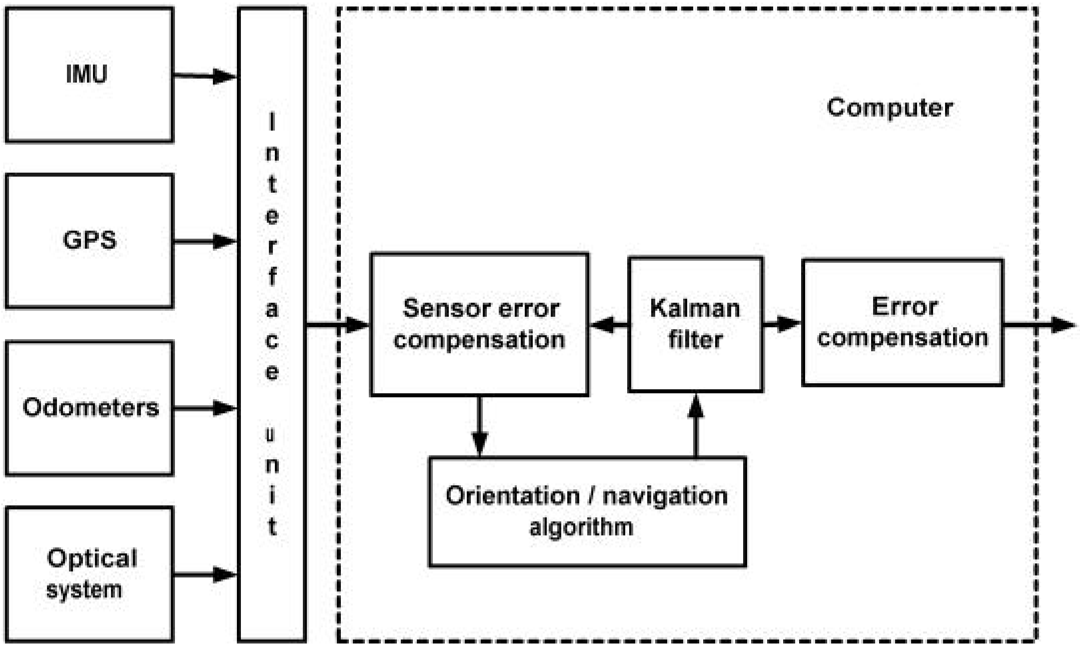

Fig.1. The structure of a vehicle road positioning system

The system includes (see Fig.1):

- **a micromachined inertial measurement unit CROSSBOW IMU400CB1** (by Crossbow Technology, Inc., USA, Fig.2). The output signals of the unit are projections of vectors of angular speed, linear acceleration, time, temperature;

- **a receiver and an antenna of a satellite navigation system** SN-3701 (by "Orizon-Navigation", Ukraine). The output data of the receiver are transmitted by the NMEA protocol and include the current time, three coordinates, the true course, the speed with respect to earth, coordinate error estimates, and a flag of data reliability;
- **two odometers** (by institute "Ritm", Ukraine, Fig.3) which generate 1024 pulses in one full revolution of the wheel;
- **an optical system for measuring the vehicle's position with respect to the road** (by institute "Ritm", Ukraine, Fig. 4) that consists of two optical sensors and a set of reflectors. The optical sensors are installed on one of the odometers. There are checkpoints on the road where one or three reflectors are installed by means of special brackets. The geometry of the brackets is chosen so that the vehicle's two coordinates, its linear speed, and the course can be determined in the checkpoints. The optical system is auxiliary and used for nothing but the estimation of the inertial system's accuracy;
- **an interface unit** (by institute "Ritm", Ukraine) to transfer the measurement results to a computer;
- **a computer, a battery, and a secondary power supply unit**;
- **a package of software** for performing the measurement and the signal processing, calibration of the system and its computer simulation (by institute "Ritm", Ukraine).

The scheme of the equipment installation in the vehicle is presented in Fig. 5 and Fig. 6.

Fig. 2. Micromachined inertial measurement unit CROSSBOW IMU400CB1

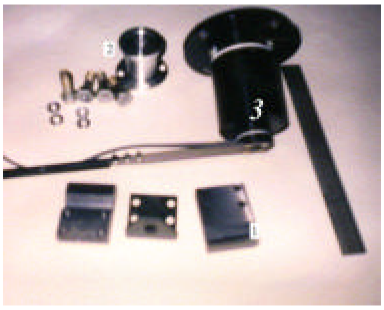

Fig. 3.
Odometer (3),
sensor of an angle (2),
elements of fastening (1)

Fig. 4.
Optical system
(1 – optical sensors,
2 – reflectors on brackets)

Fig. 5.
Layout of the equipment in a back luggage compartment of the automobile
(1-IMU, 2-power sources,
3-optical quadrant, 4-assembly plate)

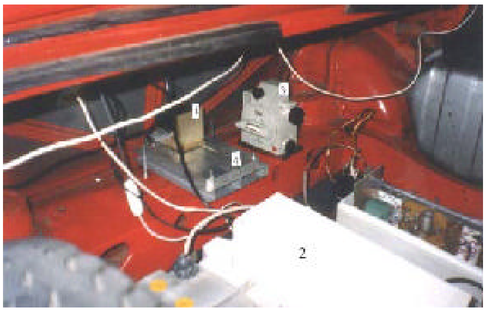

Fig. 6. Odometer fastening on a wheel

Description of software and algorithms

Principal components of the software are algorithms for sensor error compensation, orientation, calculation of the linear speed and coordinates, the Kalman filtering, and the compensation of errors of the system's output parameters.

A package of software named LOTUS has been developed for the purposes of debugging, numerical technique validation, the Kalman filter adjustment, and definition of requirements to components of the system. The package consists of two related programs: LOTUS ROAD (a simulation of the vehicle as it moves along the road of a given profile), LOTUS SENSOR (a simulation of the inertial unit, satellite navigation system, odometers), LOTUS PC (algorithms for sensor error compensation, navigation, orientation, Kalman filtering).

The computer modeling has helped us choose proper numerical techniques for the system: a one-step third-order algorithm for the orientation, and one-step second-order algorithms for calculation of the linear speed and coordinates. The systematic errors of these methods are lower by a few orders of magnitude than the instrumental errors of the system.

A closed scheme of the Kalman filter has been implemented [2,3]. The filter evaluates 24 parameters: coordinate errors (3), linear speed errors (3), errors of orientation angles in the vehicle coordinate system with respect to the geographic coordinates (3), gyroscopes drifts (3), errors of the gyroscope scale factors (3), accelerometer biases (3), errors of the accelerometer scale factors (3), odometer errors (2), the error of the traversed distance calculation performed by the inertial system (1).

The observed vector consists of 9 elements: the differences between the coordinates (3 components) and the linear speed (3 components) measured by the positioning sensors (GPS, the optical vehicle-on-the-road positioning system) and by the inertial system; the differences between the traversed distance (1 component) and the rotation angle (1 component) about the vertical axis measured by the odometers and by the inertial system, the zero speed (1 component) of the vehicle along the axis of the vehicle's rear axle.

Calibration of the system in the laboratory

The following parameters were checked and calibrated in the laboratory:

- duration of the initial warm-up of the IMU sensors after turning on the power;
- stability of the IMU internal timer;
- spectral densities and correlation functions of the gyroscopes and accelerometers;

- systematic drift of the gyroscopes and biases of the accelerometers;
- random drift of the gyroscopes and accelerometers;
- resolution of the gyroscopes and accelerometers;
- scale factors of the gyroscopes and accelerometers;
- angular mismatch between the sensitive axes of the gyroscopes and accelerometers;
- gyroscope drifts affected by the linear acceleration;
- asymmetry of the scale factors of the gyroscopes and accelerometers.

The following equipment and instruments were used:

- a small-scale rotating device MPU (Fig.7);
- an optical indexing head ODG-10 (Fig.8);
- an installation for calibrating the odometers and optical sensors (Fig.9);
- an optical quadrant and a base plate (Fig.10).

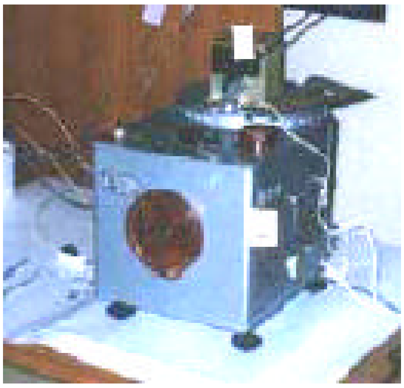

Fig. 7.
The small-scale rotating device MPU for determining the gyroscope resolution

Fig. 8.
The optical indexing head for determining the accelerometer resolution

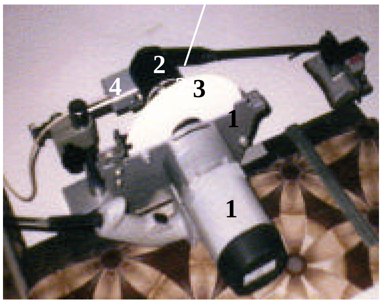

Fig. 9. The installation for the odometer and optical sensor calibration (1- a motor; 2 – the odometer; 3 – a disk with an optical reflector; 4 – an optical emitter and receiver)

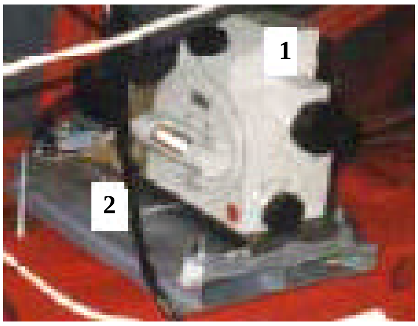

Fig. 10.
The optical quadrant (1) and the base plate (2)

Results of calibration of the odometers and the CROSSBOW IMU400CB1 inertial measurement unit's gyroscopes and accelerometers are presented in Table 1.

Table 1.

Results of calibration of the IMU gyroscopes and accelerometers

Parameter	**Measure-ment unit**	**True value**	**Rating value**
		Gyroscopes	
Range	î/s	Not determined	± 100
Drift: - on the run - from run to run	î/s	X: + 0,22 ± 0,03 Y: + 0,105 ± 0,01 Z: - 0,041 ± 0,01 X: - 0,24 ± 0,04 Y: + 0,14 ± 0,03 Z: - 0,03 ± 0,01	<± 1.0
Scale factor: - on the run - from run to run	dimension-less	X: 1,0001 ± 0.00009 Y: 1,0014 ± 0.0002 Z: 1.0010 ± 0.0006 X: 1,00006 ± 0.0001 Y: 1,0012 ± 0.0001 Z: 1.0017 ± 0.0001	Not specified
Resolution	î/s	< ± 0.001 - 0.004	< 0.025
Random drift	î/hr½	X: 0.69-0.76 Y: 0.58-0.65 Z: 2.24-2.29	< 0.85
Non-orthogonality of the axes	angular min.	–4,3 ……+ 42,0	< 60
Asymmetry of the scale factor	%	X: - 0,47...+0,34 Y: -0,64...+0,10 Z: -0,94...+0,03	Not specified
Coefficient of sensitivity to the linear acceleration	î/s/m/s2	Gyroscope X: Along X: (-65…+ 84)*10^{-5} Along Y: (-15…-5,8)*10^{-5} Along Z: (+20…+21)*10^{-4} Gyroscope Y: Along X: (+ 1…+ 6)*10-4 Along Y: (+ 5…+ 11)*10^{-4} Along Z: (-143…-142)*10^{-5} Gyroscope Z: Along X: (+14…+14.6)*10^{-5} Along Y: (+7…+46)*10^{-5} Along Z: (+139…+146)*10^{-5}	Not specified
		Accelerometers	
Range	g	Not determined	± 2
Bias: - on the run - from run to run	m/s^2	X: + 0,0283 ± 0,0026 Y: - 0,0214 ± 0,0039 Z: - 0,0093 ± 0,0045 X: + 0,025 ± 0,0019 Y: - 0,015 ± 0,0036 Z: - 0,012 ± 0,0022	<± 0,085
Scale factor: - on the run	dimension-less	X: 1,0001 ± 0.00009 Y: 1,0014 ± 0.0002 Z: 1.0010 ± 0.0006	Not specified

Parameter	**Measure-ment unit**	**True value**	**Rating value**
- from run to run		X: 1,00006 ± 0.0001 Y: 1,0012 ± 0.0001 Z: 1.0017 ± 0.0001	
Resolution	m/s^2	<± 0.0005 m/s^2 (±10”)	< 0.0025
Random bias	m/s/hr½	X: 0.037-0.074 Y: 0.037-0.062 Z: 0.038-0/061	< 0.1
Non-orthogonality of the axes	angular min.	–6,5 ……+ 8,3	< 60
Asymmetry of the scale factor	%	X: -0,75...+0,91 Y: -0,64...+1,03 Z: -0,63...+1,65	Not specified
Inertial measurement unit (as a whole)			
Instability of the internal timer	ì s	± 14	Not specified
Initial warm-up of the unit	min	20 ….. 60	Not specified

Field testing

The goal of the field testing was to evaluate the accuracy of the vehicle coordinate calculation (at the speed of up to 30 m/s) as the GPS gets silent for 5 to 10 seconds.

Field testing procedure

The field tests were run at the motor racing track (Fig. 11) of the “Chaika” sports center (Kiev). A “measuring segment” was marked up along a straight part of the racing track. Optical reflectors were installed along the path at a fixed distance which varied from 10 to 150 m (Fig. 12). The overall length of the marked segment was 550 m. The movement of the vehicle along the measuring segment is shown in Fig. 13.

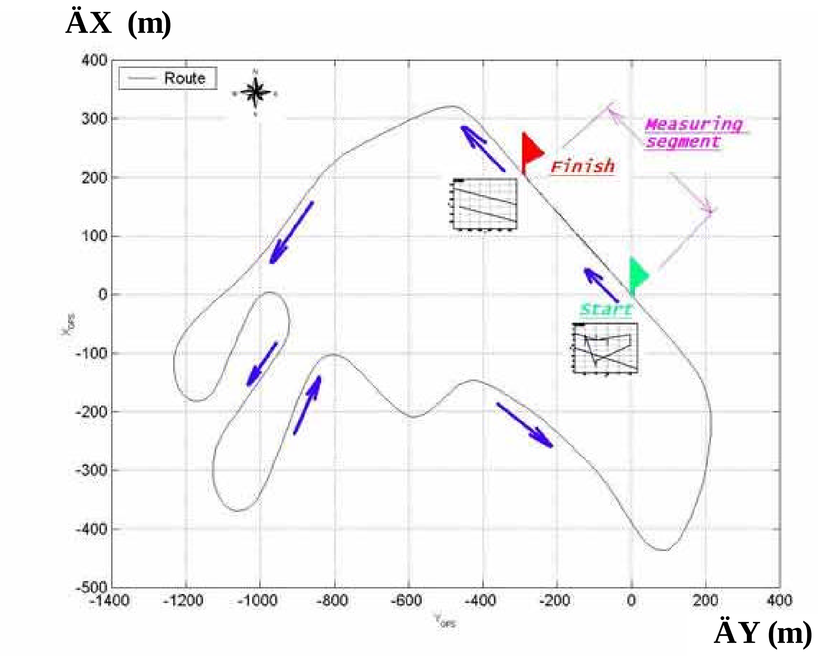

Fig.11.
A path of the vehicle at the “Chaika” motor racing track

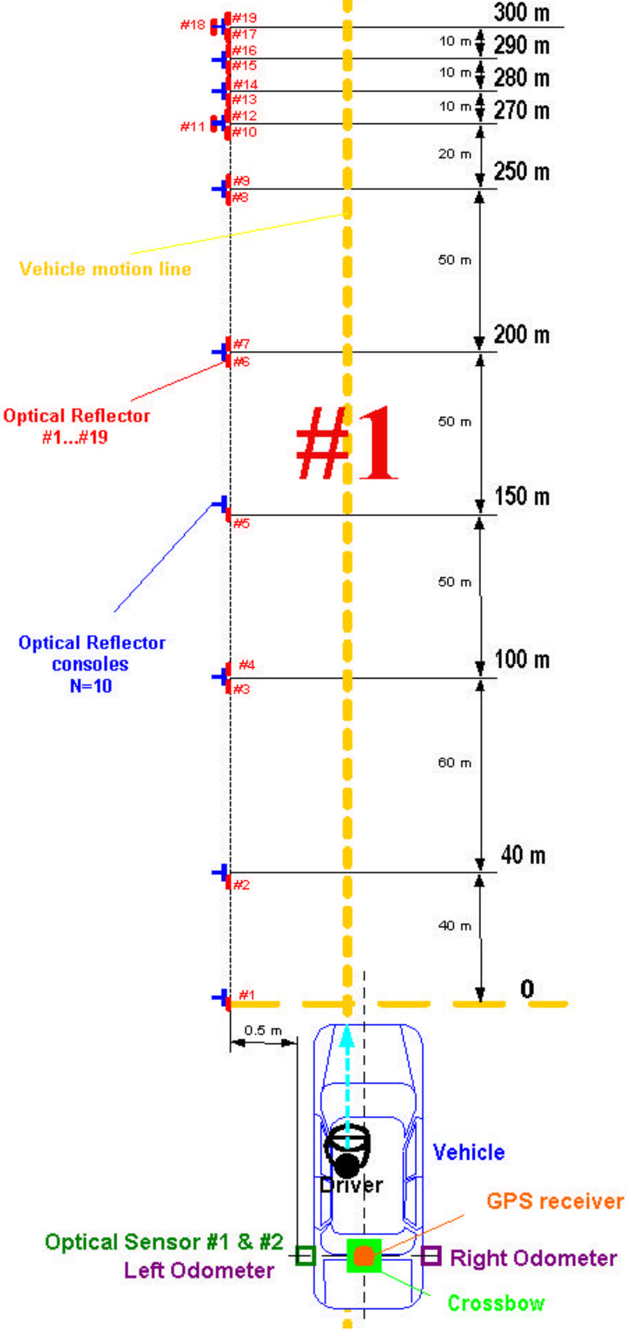

Fig.12. Markup
of the measuring segment No.1

More than twenty experiments were run at the "Chaika" track, including[1]:

- "*Odometer calibration*" (a linear movement of the vehicle along the measuring segment at the distance of 0.55 m between the optical reflectors and the optical sensors);
- "*Movement at the maximum speed*" (a linear movement of the vehicle at a maximum possible speed along the measuring segment);

Fig. 13. Movement of the vehicle along the measuring segment

- "*Serpentine movement*" (a curvilinear movement between the optical reflectors in the measuring segment);
- "*Departure from the straight line*";

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[1] The italicized text marks informative entitlements of the experiments.

- *“Loop around the “Small circle*”;
- *“Loop around the “Big circle*”;

Each of the listed experiments was repeated at least three times and consisted of three phases: (1) arrival of the car at its initial position (the Start point); (2) turning the sensors’ power on[2]; (3) standing still with the motor shut down (60 to 100 sec); (4) start of the movement; (5) passing the measuring segment; (6) movement along the track to the Finish point.

A synchronized recording of the following output signals was performed in real time during the experiments:

- those from the inertial measurement unit at the frequency 134 Hz in the time scale of the unit’s internal timer;
- those from two odometers installed on the right and left wheels of the vehicle, at the frequency of 134 Hz in the time scale of the interface unit;
- those from GPS at the frequency of 1 Hz in the time scale of UTC;
- those from the optical system of the vehicle-on-the-road positioning system (moments when the output pulses from the optical system’s sensors arrive) in the time scale of the interface unit.

Results of field testing

1. Calibration of odometers

After results of three “Odometer calibration” experiments, scale factors of both odometers were calculated (Table 2).

Table 2.

Average and standard deviation of the odometers’ scale factors

Left odometer		Right odometer	
Average	Standard deviation	Average	Standard deviation
0.0016725040	0.00003498244	0.0016720668	0.00003469998

2. Measurement of the vehicle’s trajectory by the system

Fig. 14 presents a trajectory of the vehicle’s motion measured by GPS (the top plot) and that calculated by data from the inertial measurement unit, odometers and the optical system (the bottom plot).

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[2] The power supply of the inertial unit was turned on before the experimentation day, and its sensors were warmed up for 1 hour; the power was turned off only after the day of experimentation was over.

3. Errors of the coordinate calculation without the silence of GPS and the optical system

Fig. 15 presents typical time histories of the errors of calculation of the longitudinal and lateral coordinates of the point where IMU is installed in the vehicle. They were obtained by aggregation of data coming from the inertial measurement unit, odometers, GPS, and the optical system. It can be seen in this figure that the filter performed a calibration and an error compensation of the unit during the transition period (200 to 220 sec), and then the system would determine the coordinates at the accuracy (3ó) of 10 to 15 cm.

Analysis of results of the “Movement at the maximum speed experiments” (Fig. 16) shows that the system ensures the maximum error of the longitudinal coordinate calculation (3ó) to be not greater than 1.0 m and that of the lateral coordinate not greater than 0.15 m at the speed of the vehicle up to 30 mps with the normal reception of GPS satellite signals.

4. Coordinate calculation errors after silence of GPS and the optical system

Fig. 17 presents typical time histories of the errors of calculation of the vehicle’s longitudinal and lateral coordinates when the short-time (5 to 7 sec) silence of GPS and the absence of information from the optical system are simulated[3].

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[3] Figs.16 and 17 present results of post-run processing of the same experiment but in different condition of GPS’ and the optical system’s visibility.

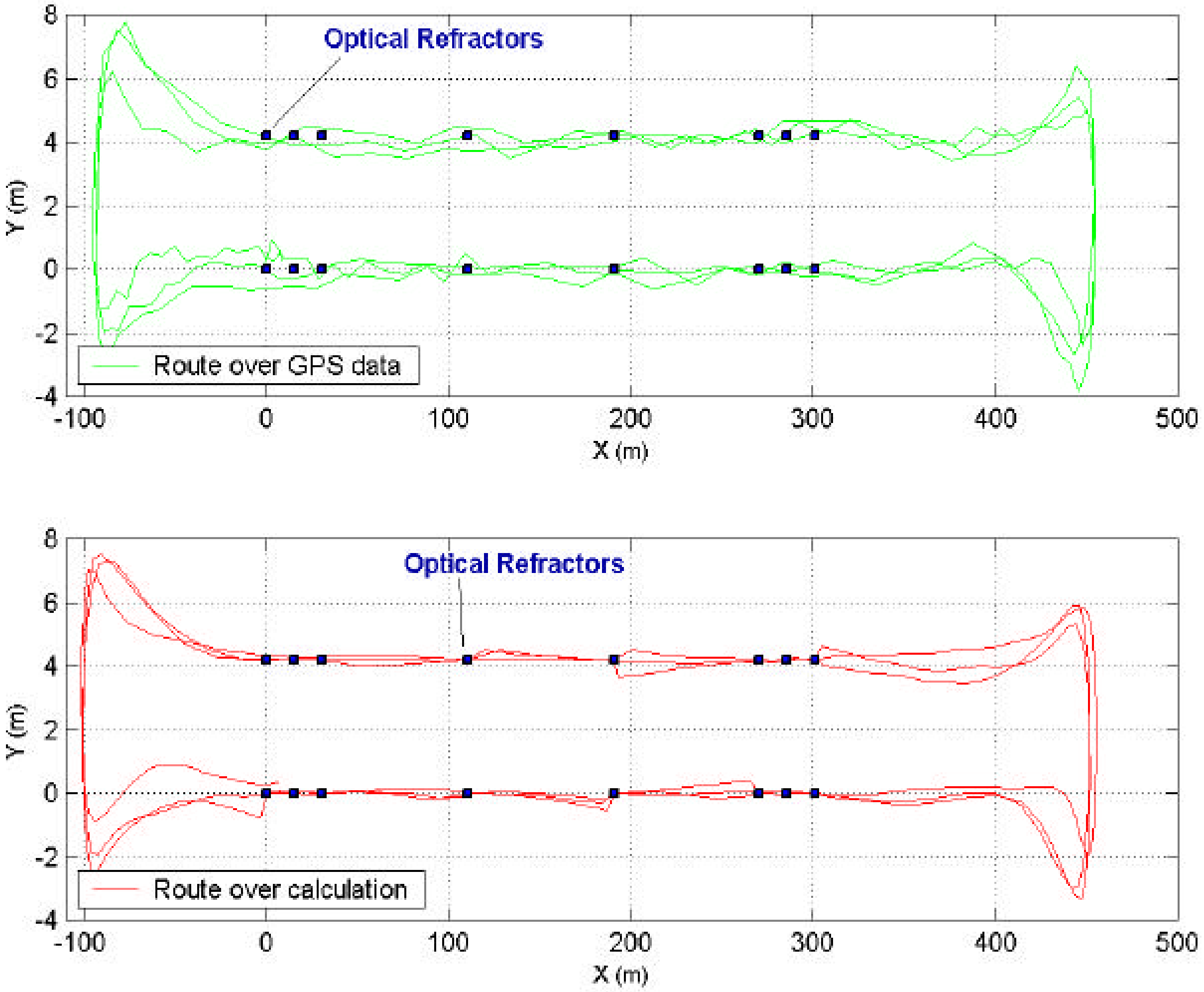

Fig.14. The trajectory of the movement measured by GPS and the inertial positioning system of the vehicle (the “Odometer calibration” experiment)

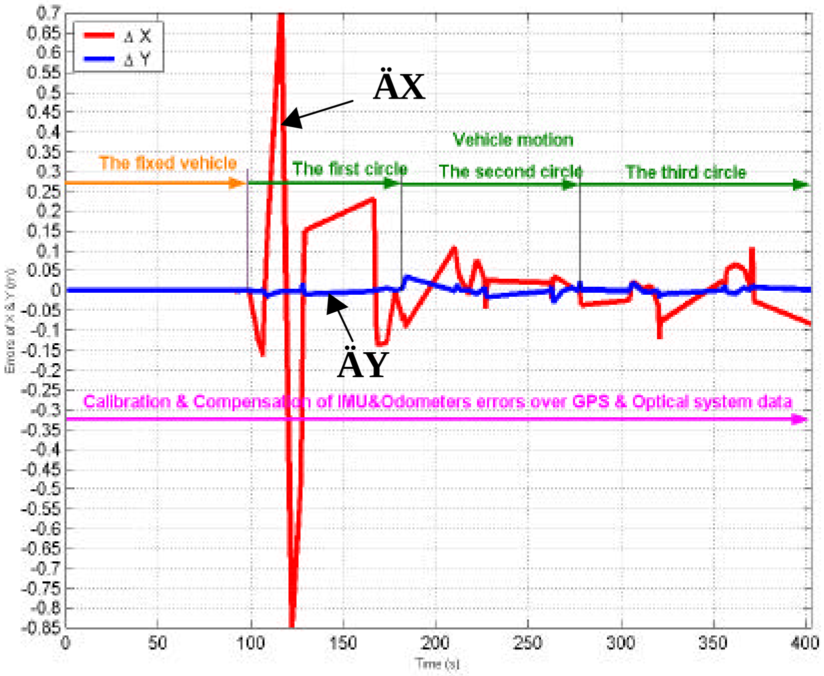

Fig.15. Errors of calculation of the longitudinal (ÄX) and lateral (ÄY) coordinates of the vehicle obtained by aggregating the data from IMU, odometers, and GPS (after results of the “Odometer calibration” experiment)

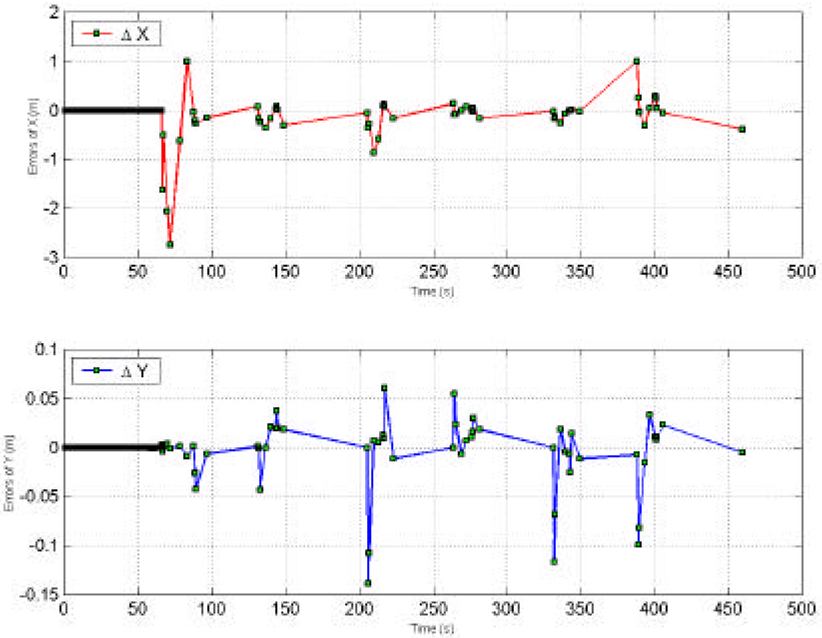

Fig.16. Errors of calculation of the longitudinal (ÄX) and lateral ÄY) coordinates at the vehicle’s speed up to 30 mps (after results of the “Movement at the maximum speed” experiment)

Analysis of results of all experiments which have been run shows that the system can provide the error of the longitudinal coordinate calculation no greater than 0.65 m (3ó) and that of the lateral coordinate no greater than 0.90 m (3ó) at the speed of the vehicle up to 30 mps, at short intervals of time (5 to 7 sec) when GPS satellites are not intercepted.

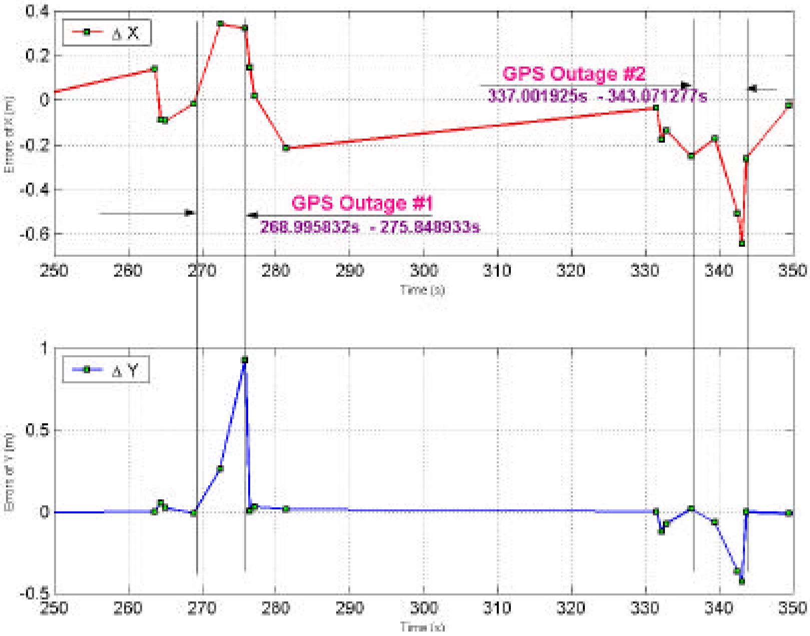

Fig.17.
Errors of the longitudinal (ÄX) and lateral (ÄY) coordinates in the absence of signals from both GPS and the optical system (the experiment "Movement at maximum speed")

Conclusion

The aforesaid experiments have shown that the hardware and software developed by us and based on micromachined inertial sensors provide the admissible error (RMS 20..30 cm) of the vehicle's relative coordinate measurement during (5-7) sec of the satellite silence at the vehicle's speed 20 to 30 mps. At subsequent stages of the project, it would be reasonable to investigate the possibility for creation of cheaper inertial measurement units taking into account specifics of their operation and particular tasks performed by vehicle safety systems.

Acknowledgements

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