Development and evaluation of GPS aided strapdown INS for land vehicles by means of a Kalman filter

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Abstract – **A real-time land vehicle navigation system has been developed. It consists of a GPS receiver and a low-cost inertial block with three axis accelerometer and a yaw rate gyroscope. A time synchronization algorithm is presented. A Kalman filter has been designed and its performance has been evaluated and tested in MATLAB. Two different models of inertial sensors are implemented and tested with real-world experimental data. The aim of the paper is to present a hardware structure of low-cost GPS/INS system for land purposes and outline the main principles and algorithms of the systems' integration and data fusion process.**

Keywords – **Land vehicle navigation, GPS, inertial sensors, Kalman filter**

I. INTRODUCTION

The Global Positioning System (GPS) has made navigation systems practical for a lot of land-vehicle navigation application. Although the purpose of GPS is to provide location in 3D space, in general, a land-vehicle navigation system cannot continuously position using a GPS alone due to the lost of GPS signal in urban environment or in tunnels. Inertial navigation system (INS) is independent and autonomous system. This fact makes is very suitable to complement the GPS shortcomings.

The main problem of the INS is the accumulation of error in velocity, position and angle with time because of the double integration of its data [1].

The fusion of GPS and inertial sensors has been used in various applications [2-4] and the most often used method for the fusion process is the Kalman filter. Integrated GPS/INS can be implemented in different modes: loosely, tightly and ultra-tightly coupled [5].

The integration mode used in this paper is from the first type, where the GPS data is used for calibration of the inertial sensors while the GPS signal is available. The main idea is to implement and evaluate a GPS/INS with very low-cost sensors - inertial devices used [6, 7] have a total price of about $50.

Some real-world experiments were carried out and presented in the paper. The Kalman filter was implemented in MATLAB and two models of the inertial sensors have been implemented and tested.

II. HARDWARE DESIGN

The developed integrated GPS/INS system consists of two main blocks: inertial (Fig. 1) and navigational (Fig. 3).

The inertial block measures the linear accelerations on the three axes and the angular rate in the ground plane.

For full 3D navigation a single gyroscope is not enough but because of the purpose of the system – land navigation, only one gyroscope is implemented.

A very precise analog to digital converter AD7739 [8] was used in this design to minimize the errors from conversion of analog outputs of the sensors to digital data. The MCU takes care of the synchronization of measurements and transfer of gathered inertial data to the other block.

The inertial block's algorithm has been developed to make measurements with frequency of 10Hz which is quite enough for land-vehicle applications [2]. For such an integrated system it is very important to keep it synchronized while working.

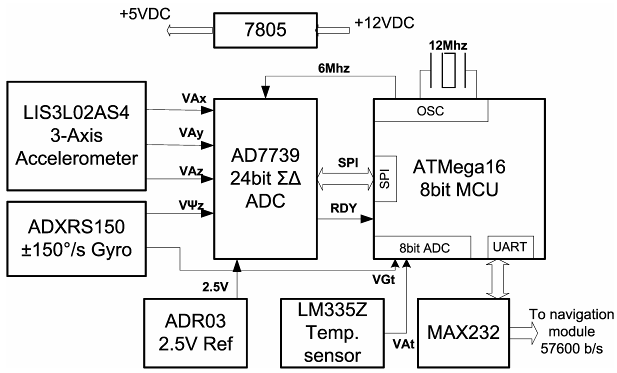

Fig. 1. Block diagram of the inertial sensors sub module

Two types of synchronization have been experimented: single synchronization at the begging and "per-PPS" synchronization on every PPS pulse from the GPS receiver. The first one has insufficient preciseness because of the limited accuracy of the quartz crystals used in both blocks. The difference in frequencies of the crystals causes unbounded increase of the time difference between the measurements of both systems which is unacceptable.

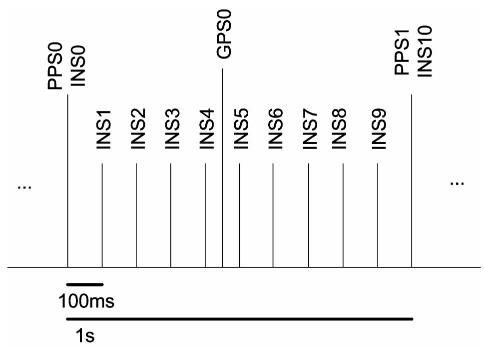

Fig. 2. "perPPS" time synchronization between modules

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The synchronization scheme, proposed on Fig. 2, is used in the system. The navigational block initiates measurement cycle in the inertial block at every PPS pulse. The initiation is implemented via sending a special “start” character from the navigation module to the inertial one. The time offset introduced by the time for sending the “start” character depends only from the baud rate of the RS-232 link. The selected speed of 57600bps gives a time offset of:

$$\Delta T_{SYNC} \approx 0.174ms\,.$$

The measurement cycle consists of 10 consecutive measurements of the inertial data set (ax, ay, ax, ψz). A special continuous conversion mode of AD7739 is used which gives a total time for conversion of all the channels of 4ms with channel bandwidth of 500Hz. Every next block of 10 measurements overlaps the previous thus a continuous series is obtained and it is synchronized with the GPS data. Obviously, the ΔT_{SYNC} value is quite small in relation to the ADC conversion time and any error introduced by this parameter can be neglected.

Fig. 3 shows the structure of the navigational module. It is based on powerful ARM7 MCU which handles the tasks for GPS coordinates processing and communications with the GPS receiver and the INS module. Although the MCU do not have floating point unit it is also capable of processing a simple Kalman filter.

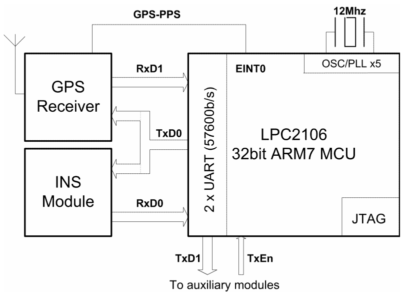


Fig. 3. Block diagram of the navigational sub module

III. DATA FUSION

The first step to integrate both systems is to select a common coordinate system. The assumed plane motion makes the NED frame the most suitable, because inertial data is directly integrated in it. System state in NED is defined as follows (the notation used is from [11]):

$$x_k = [x, y, v, \theta]^T\,, \tag{1}$$

where *x, y* are the vehicle coordinates in the north and east directions, *v* is the ground speed, θ is the course over ground. Again from the plane motion, the *z* coordinate (down direction in NED) is assumed unchanging while short-term navigating.

The measurement vector (from GPS) has the same form and it is:

$$z_k = [x_{GPS}, y_{GPS}, v_{GPS}, \theta_{GPS}]^T \tag{2}$$

The relation between consecutive time steps in the system state has the following general form:

$$x_{k+1} = x_k + \begin{bmatrix} v_k \cos\theta_k \Delta t \\ v_k \sin\theta_k \Delta t \\ a_k \Delta t \\ \psi_k \Delta t \end{bmatrix}, \tag{3}$$

where $u_k = [a_k, \psi_k]^T$ is the system’s driving function built from the linear acceleration and the rotation rate of the vehicle in the plane of motion. $\Delta t = 100ms$ is the time interval between measurements.

An Extended Kalman Filter, based on the algorithm described in [11] and equations from (1) to (4) is built. The initial value x_0 is determined with the help of the GPS receiver:

$$x_0 = [0, 0, GSPD, COG]^T\,, \tag{4}$$

where GSPD is the ground speed reported from GPS and COG is the corresponding course over ground at the starting point P_0 of the integration of the systems.

Equation (3) presents only the general form of the navigation equations when inertial sensors are assumed ideal. Two different models of the inertial sensors have been tested with the filter. The first model is a simple one [12], concerning only the bias and the scale factor of the sensors as constant values. For the accelerometer (the same form is also used for the gyroscope sensor) it has the following form:

$$a_k = (a_1 + a_2 . \hat{a}_k)\,, \tag{5}$$

where a_1 is the bias, a_2 is the scale factor, $\hat{a}_k$ is sensor’s output, a_k is the “true” value of the acceleration.

The second model evaluated is proposed in [3] and it is based on exponential functions. It has the following form for the accelerometer:

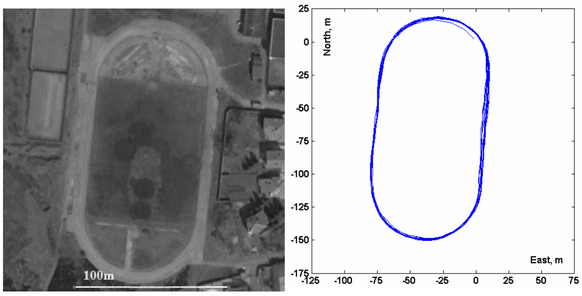
$$a_k = (a_1 + a_2 e^{a_3 t}) + a_4 . \hat{a}_k\,, \tag{6}$$

Experiments with the sensors, used in this design, show that such an exponential processes are also observed in their output.

IV. PERFORMANCE OF THE MODELS IN REAL-WORLD EXPERIMENT

To validate the performance of both models a real time experiments have been carried out. The circular shape of trajectory is known [4] to provide the best performance in determining the horizontal accelerometer biases. Thus a stadium (Fig. 4) is selected as reference trajectory because its shape is very close to the circular.

The selected place for experiments is also suitable because stadiums have very low level of slope so the assumption of plane motion (without giving an account of the *z* coordinate in NED) is more trustworthy. The beginning of the NED (P_0) coordinate system is defined near the center of the northern arc of the stadium (Fig. 4b). The presented experiment consists of 600s continuous driving along the stadium.



a b

Fig. 4. Google Earth's image of the reference trajectory (a) and the corresponding GPS location data in NED (b)

To simulate GPS outage in specified moment, the "measurement update" process is stopped and the EKF continues to perform only the "time update".

The model from Eq. 5 has been evaluated with eight state EKF (the system states from Eq. 3 plus four parameter of the two sensors). To illustrate the estimation of the filter of the sensor's parameters (a_1 and a_2) the simulation is first started with uninterrupted GPS signal. Fig. 4 shows how the filter works on the estimation of the parameter trough the whole driving process of 600 seconds. It is obvious that some of the parameters do not tend towards some constant value and changes all the time. This change is due to the very simple nature of the model and hints that the assumption of constant bias and/or scale factor is not absolutely true. The same conclusion applies also from investigating the diagonal elements of the error covariance matrix: the corresponding error covariance of the changing parameters does not tend (or tend slowly) to a constant value.

A simulation of GPS signal outage has been carried out and the result of the calculated route is shown on Fig. 6. The GPS signal is "stopped" on the 300[th] second and the navigation remains only inertial using the last estimated sensors' parameters. Even very simple, the model shows good results for the low-cost sensors used. It is well noticeable that the gyroscope is more badly modeled and gives a constantly increasing error in the course over ground. At the end of the inertial navigation the amplitude of the position error in north and east directions reaches about 50m.

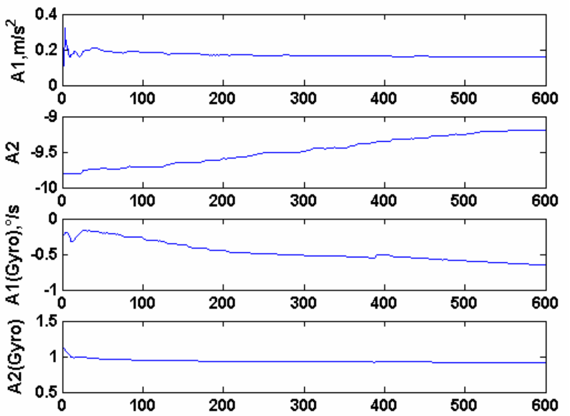


Fig. 5. The estimation process of the sensors' parameters with the aid of GPS data and EKF

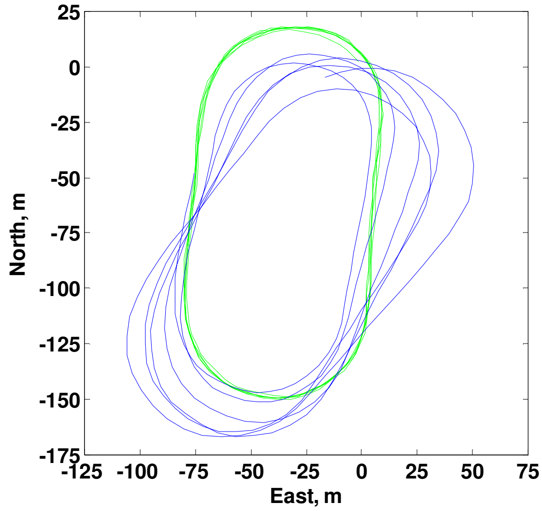


Fig. 6. Performance of the first model when only inertial navigation remains

The second model from Eq. 6 has been tested in the same circumstances. The composed EKF in this case comprises twelve states. The inertial only navigation (Fig. 7) shows better performance in relation to the previous model. Especially the gyroscope performance is improved and course over ground diverges slightly. At the end of the inertial navigation the amplitude of the position error in north and east directions reaches about 25m.

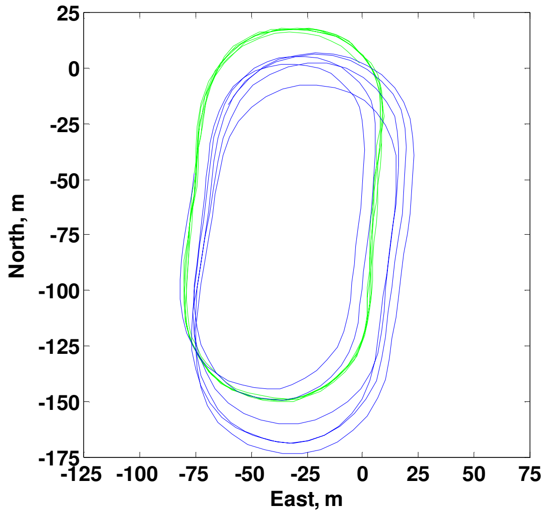


Fig. 7. Performance of the second model when only inertial navigation remains

The exponential model typically shows better performance because it is closer to the real-world sensor's performance but it will require more processing power. For filtering outside the real hardware system the size of the system state is not a concern, but when implementing different models they must be carefully judged to match the available calculating power of the system. Thus for a simpler systems, although it's lower performance, the first model is also applicable due to the smaller size of the system state.

V. CONCLUSION

A hardware design of an integrated low-cost INS/GPS system is proposed in this paper with a time synchronization scheme without time difference accumulation between two systems. An Extended Kalman filter is also synthesized for the data fusion and estimation of the sensors' parameters using GPS as a reference system. Real-world experiments have been carried out to validate the integration process and the performance of two different models for inertial sensors.

The investigated models both show that inertial only navigation can continue for more than 300s with error in position of 25-50m using very low cost inertial sensors and the standard GPS service. The implementation of such a system for a real urban route will require a lot of additional parameters to be considered, like temperature, the slope of the plane of motion which introduces static errors in accelerometers. Thus once has to look at this research more like theoretical approach although carried out with real-world experiments data.

The main contribution of this research work is in the founding of theoretically-experimental setting for evaluation of INS/GPS integrated systems, development and testing different models of the inertial sensors. The author's future effort will be focused namely on the research for more suitable and detailed inertial sensors' models, covering more factors of influence.

VI. REFERENCES

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