MEMS Electromechanical Microsystem as a Support System for the Position Determining Process with the Use of the Inertial Navigation System INS and Kalman Filter

Lucjan Setlak and Rafał Kowalik
Aviation Division, Department of Avionics and Control Systems
Polish Air Force University
Deblin 08-521, ul. Dywizjonu 303 No. 35
Poland
l.setlak@law.mil.pl, r.kowalik@law.mil.pl

Abstract: - The article attempts to present a technological solution based on the use of the integrated MEMS system technology, necessary to make measurements of the positioning system, built using inertial navigation sensors (INS) and the Kalman filter and the GPS receiver. As inertial sensors, low cost, commonly available accelerometers, magnetometers and gyroscopes made in MEMS technology were used. Among others, the way of calibrating the accelerometer and methods of processing signals from MEMS sensors were discussed. The main goal of the work was to develop an integrated MEMS system, which is also a supporting system together with the inertial navigation system and the Kalman filter in the aspect of determining the position of a flying object. The article presents the essence of the MEMS technology used in terms of accelerometric measurements and discusses the phenomenon of unbalance in the INS system, measured using an accelerometer. The mathematical model of the measurement of the position of a potential flying object was presented along with the inaccuracies that occurred during the measurement. The accelerometers were calibrated and tested for the first time in the area of non-linearities of their scaling factors, and then determined at a defined level, which performed repetitive maneuvers of movement in a straight line. The results of computer simulations carried out in the Matlab/Simulink programming environment were also presented. Based on the analysis and selected simulation tests, practical conclusions resulting from the research were formulated. The research results prove the potential for using MEMS technology in the area of GPS positioning systems.

Key-Words: - Electromechanical microsystem, support system, inertial navigation system (INS), Kalman filter

1 Introduction

Analyzing the electromechanical microsystem MEMS *(Micro-Electro-Mechanical System)*, it should be noted at the outset that with the dynamics of inertial development of the navigation system INS *(Inertial Navigation System)* together with the Kalman filter, it plays a key role in determining the position and positioning in the space of flying objects (aircraft, helicopter, unmanned aerial vehicle) [1], [2].

Contemporary technological solutions in the field of aircrafts navigation, based on the inertial navigation system INS is a well-recognized and well-defined technology used since the 1960s in advanced American military devices in the form of ships, submarines and various types of aircraft.

The main idea of the functionality of the INS system is based on the acceleration measurement process and the rotation angle in all three directions. In turn, having information about the initial location and orientation, one can determine the location of one's position. However, modern technological solutions in the field of navigation are limited in terms of accuracy.

Inertial system INS with position drift contained in the range of 0.5-0.25 NM/h *(Nutical Mile per hour)*, i.e. about 1.61 [km/h] is considered a good quality system, this drift is usually the standard level of accuracy used in objects such as, for example, a long-range aircraft. This type of system is very expensive to buy, reaching tens of thousands of dollars.

In comparison to their competitors, which are gimbal systems, they usually achieve higher maintenance costs due to their mechanical complexity, as the inertial systems without gimbals naturally have lower maintenance costs and failure rates due to the smaller number of moving parts.

It should be noted that navigation is a concept that is contained in three different areas, namely: the first area of navigation is location, the second is planning the road, and the third is going along the planned road. In addition, the basic principles of aircrafts navigation are initiated and analogous to marine navigation [3].

Currently, more advanced methods and navigational instruments are used, although astronomical navigation was still largely used in aviation of the twentieth century, ultimately it was replaced by the GPS *(Global Positioning System)*.

1.1 GPS system

The emergence of the GPS navigation system has enabled potential users to purchase an accurate and low-cost navigation system (compared to the INS system), however, susceptible to jamming in the form of *jamming* and other interruptions in the signal.

The GPS system includes many satellites circulating around the Earth, monitored and supported by a network of ground stations. Such satellites send signals received by GPS receivers, which subsequently use signals to determine the distance of the receiver from the satellite.

It should be noted that if enough satellites are available (minimum four), the receiver performs multilateration to determine its position on (or above) the surface of the Earth, while the uncomplicated, inexpensive GPS receiver can achieve accuracy approx. 10 [m] or less.

Multilateration is a type of navigational technique that amounts to measuring the difference between distances to min. two stations, located in well-known locations broadcasting a spread signal (in a propagated form) at specific moments of time.

In terms of the functionality of the operation, the GPS system is designed to determine the spatial location of the points on which the apparatus is set up to receive radio signals sent by the artificial satellites of the Earth.

Its operating principle is based on determining the location of a given terrestrial point by measuring the time of reaching a radio signal from satellites to the receiver. In turn, knowing the speed of the electromagnetic wave, one can calculate the distance from the receiver to the satellite.

Global positioning system GPS is a system based on satellite navigation. The distance is calculated based on the time of the radio signal from the satellite to the potential user's receiver.

However, knowing the signal travel time and the speed of the electromagnetic wave from at least four satellites, the receiver is able to calculate latitude, longitude and the ellipsoidal height of the object.

However, the GPS system is exposed to a large number of errors from various sources, which can be divided into two main groups: cosmic segment errors, i.e. atomic satellite clock error, orbital, ionospheric and tropospheric error, and user's segment errors (receiver), which can be user's clock error, multipathing and interference.

1.2 Integration of GPS/INS systems

By integrating the GPS system with the INS system together with the use of filtering properties of the Kalman filter, it is possible to obtain a more accurate GPS navigation solution, while maintaining the reliability of the INS system. In turn, the obtained reliability will ensure the measurement of the position, and thus the functionality of the integrated system in the event of breaks in receiving a signal from the GPS system.

Another advantage of combining (merging) the above systems is that the systems under consideration mutually complement each other, i.e. each system very well complements the weaknesses of the other, e.g. the GPS system has excellent low frequency performance but weak in the high frequency range. The obtained error of 1-2 [s] in the indicated position has the ability to change even within a few meters, whereby in long periods of time the position error maintains a relatively constant value.

However, the INS system has very good performance in terms of high frequency, but at the same time it is characterized by poor performance in the low frequency range. In addition, for a very short period of time, the error specified in seconds changes very little, while within a few minutes or even hours, the position drifts significantly to the order of kilometers. The combination of integrated INS/GPS systems combines the advantages of both systems and achieves very good results in the low and high frequency range [4].

The Kalman filter is a common way to implement this type of integration, and there are several different levels of integration. The loosely coupled system is characterized by the fact that it integrates the position with the INS system with the position given by the GPS receiver. It should be noted that this is the easiest solution to implement, but it resigns from some of the advantages of closer integration.

The strictly coupled system uses raw pseudorange data acquired from the GPS receiver and acceleration measurements from the 3-axis accelerometer and the angular velocity of the 3-axis gyroscope, which are components of the inertial navigation unit IMU *(Inertial Measurement Unit)*.

The integration of the two systems in such a strictly defined manner ensures better results, enabling the INS system to support the GPS receiver monitoring loop and allows the entire system to use GPS data even when fewer than four satellites are available.

The block diagram of a closely related implementation is presented in the figure below (Fig. 1).

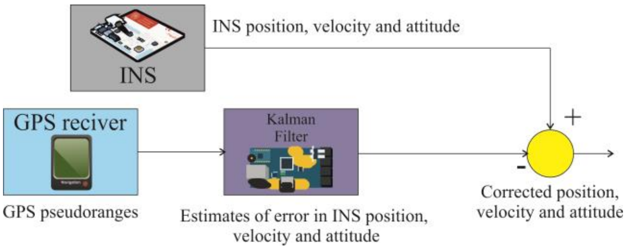

Fig. 1 Block diagram of GPS/INS systems integration

In the aspect of the subject of the examination under consideration in this article, there is also a very close coupling that uses data from the IMU and the GPS receiver in its most raw form [5]. Usually, the task of determining the position and height of a potential flying object (e.g. an aircraft), boils down to an automatic control operated by combining an inertial measurement unit (IMU) with the receiver of a global positioning system (GPS).

In this configuration, both accelerations and angular velocities from the IMU can be integrated in time, and position updates from the GPS system can be used to reduce errors resulting from this connection [6], [7].

This kind of solution to the problem of navigation makes the aircrafts vulnerable to failures in certain ranges due to their dependence on external signals reception from the network of the GPS system. Signals from the GPS system may be disturbed or suppressed in congested environments, and the reception of these signals may also be blocked or otherwise prevented.

For example, it should be noted that basing on the reception of GPS signals imposes artificial restrictions on the flying object in the form of UAV *(Unmanned Aerial Vehicle)*, which can physically operate in enclosed spaces, in crowded or unfriendly conditions.

A navigation system that can only function with a combination of inertial and vision sensors would be a fully autonomous system that would also not be vulnerable to blocking or detecting. Similarly, the task of mapping the surrounding environment is commonly implemented using sensors with a wide range of scanning areas of interest.

However, these sensors typically consist in emitting and receiving a signal to determine a range that may be undesirable if the potential object requires undetection. In recent years, it has been proposed that adding an IMU unit to the vision system would help in the development of these algorithms, because the inclusion of inertial sensors allows to predict the movement of the camera from the frame to the frame, and also helps in resolving the ambiguity of the scale.

In summary, the key goal of integration is to achieve even greater efficiency of the combined INS/GPS system, but this extremely tight integration technique is still quite new and not fully developed. This also requires access to the internal loops of GPS receiver monitoring, which is not always possible.

A combined system, integrated into one from the described methods, is much more accurate than the independent INS system, but due to the cost of a standard IMU unit, its cost is still too high to be practical in common use.

The next part of the article presents the MEMS system, which is a tool supporting the determination of the position of a flying object in terms of potential practical application and the adopted assumptions of the integrated system.

2 The MEMS System as a Supporting Tool for Determining the Position of a Flying Object

Modern technological solutions of the MEMS system have enormous potential in the field of navigation, and one of the key advantages is the low cost of their operation. The MEMS system devices are mass produced in very large quantities, as a result of which their unit cost is relatively low. Another important advantage is their economical saving in terms of weight and space.

MEMS system devices are characterized by increasing measurement errors, that is why in the first stage of the inertial navigation algorithm, moments are searched in which the variance of progressive and rotational speed is low, which will allow estimating the error of the data offset from measuring devices (sensors) [8], [9].

Gyroscopes and accelerometers can be large and heavy devices, while the MEMS versions of these devices are incomparably smaller and lighter. In addition, the inertial devices of the MEMS system also have much lower power requirements than their full-size counterparts, making them ideal for mobile applications.

In turn, the main disadvantage of MEMS system devices, at least at the current stage of their technological development, is poor performance compared to standard devices and inertial systems.

For example, the use of a gyroscope is a factor limiting the accuracy of the INS system, the MEMS inertial sensors are similar in this respect, because gyroscopes in MEMS systems also limit the accuracy of navigation. However, this kind of technology is developing at a fast pace and studies are still underway.

Currently, several IMU units are being developed in the field of MEMS system for military applications, among others Honeywell (HG-1900) or others that are also available on the commercial market [10], [11].

2.1 Potential practical applications of the integrated INS/GPS system

Awareness of the need to make the navigation systems resistant to possible electromagnetic interference is one of the elements of the construction process. However, it should be emphasized that while constructors manage to increase their resistance to confusing interferences, they are not able to provide functionality of operation during influence of strong blocking interferences.

Such a disadvantage of radioelectronic systems causes that one of the solutions guaranteeing the improvement of the operation of navigation systems is the integration of sensors acting using various work rules, including also autonomous devices.

Such devices are, among others INS inertial systems, using sets of gyroscopes and accelerometers. Depending on the technology used, they differ not only in the quality of the measurement but also in the price. Integration of the INS system and the GPS receiver is treated as a system, in which the navigation elements are calculated, such as location, speed, spatial orientation and time, with no feedback in the integrated system [12], [13].

Integration of the INS/GPS system, which uses the IMU unit in the MEMS technology, provides significant savings that allow the system to be used in many different applications. One of such applications is the navigation of an object (e.g. a vehicle). GPS systems are already in use for this type of navigation systems, but as vehicles move under bridges, near or under natural obstacles, such as trees or in urban environments, GPS signals are lost or blocked.

Thanks to the combined INS/GPS system, the INS system can continue to track the position of the vehicle until the GPS signal is received again (and if necessary provide information on the course and orientation of the vehicle). Another possible application is testing catapult seats, for which the trajectory and position must be tracked and recorded.

It should be noted that the integrated INS/GPS system would be much more efficient and much cheaper than the current camera-based tracking system used in aviation. The third application is used to track the orientation and location of large on-board antennas that are used for precision landing systems on aircraft carriers [14].

Another example concerns night vision goggles, which would have pre-mapped information about the area imposed on the user's sight, because such a system would have to know the position and position of the user's head. In short, any system that could benefit from navigational information would have a cheap solution available.

In summary, combining them with satellite systems receivers creates integrated INS/GPS navigation systems that guarantee high accuracy at an affordable price. The only problem is possible electromagnetic interference, which in the event of a system in the range of interference can definitely reduce the quality of the system.

The problem to be solved is to assess the quality of system functioning in such a situation, and in the case of disturbances, identification of such a situation and a corresponding limitation of confidence in its operation.

2.2 Assumptions of the integrated system using the Kalman filter

The main purpose of this article is to conduct research in the aspect of tight integration of the INS/GPS system in real time using the IMU unit in MEMS technology, where the MEMS system is indicated due to its associated advantages with costs and dimensions. The INS/GPS system should be tightly coupled due to the efficiency advantage it provides over a loosely coupled system with one or two feedback loops.

The system with a single centralized Kalman filter is referred to as a strictly integrated system in which the INS system and the GPS receiver are treated as sensors providing unfiltered measurements of pseudorange and pseudorange changes, as well as linear accelerations and angular increments.

This kind of solution complicates the integrated system, but it allows to obtain significant benefits.

In a tightly integrated INS/GPS system there is no problem of processing pre-filtered navigational data, which eliminates accuracy problems and stability typical of cascade filters.

An additional advantage of the integrated system in this way is the ability to use data from the GPS receiver, even if it tracks too few satellite signals to determine the user's location itself.

In addition, close coupling is also less computationally-intensive than ultra-close coupling, defined as *deep coupled* or *ultra-tightly coupled*, which combine in one algorithm the signal tracking function of the GPS receiver and the common INS data processing function and GPS receiver.

It should be noted that an ideal end result is a component that can be easily integrated into another system by providing data location, speed and orientation in a standard digital format to ensure maximum system interoperability.

This type of arrangement would be a unique system, with few people if in general, anyone analyzed the wide functionality of integrated real-time navigation, i.e. integration of the INS/GPS system, which uses the low-quality MEMS system of the IMU unit as the basis, where cost, power and size are also like accuracy, important factors in the development process of such a device.

For this purpose, this work describes development and testing the MEMS integration algorithm of the IMU/GPS system using the Kalman filter, implemented in the final processing stage, where the implementation of these algorithms in the real-time system gives promising results.

The Kalman filter is a technique based on stochastic system modeling, which can be applied to the problem of control or data processing, when deterministic models and techniques are not sufficient, there are several reasons why the deterministic model would be insufficient.

First of all, no mathematical model of the system is perfect, and the stochastic model of the system provides some modifications to the system variants and unmodified effects.

Second, dynamic systems are driven not only by control inputs, but by internal and external interference that can not be modeled or controlled methodically.

Thirdly, system sensors do not provide accurate data, where the data is affected by noise, and the sensors provide incomplete information and have inherent errors, such as inclination or non-linearity.

In addition, stochastic modeling is much more effective than deterministic techniques in dealing with these system realities.

The Kalman filter is best described as so-called "optimal recursive data processing algorithm" [15]. It is optimal in many respects, one of which is that it uses all available data, regardless of their quality. It is a recursive filter because it takes into account the effects of all previous data, without requiring the storage and reprocessing of all old data every time new data is available.

It is also a data processing algorithm, usually in the form of a computer program run by a central processor, not an electrical filter, e.g. a "black box".

One main assumption is the basis for the Kalman filter, which assumes the existence of an appropriate model of the real system (in the form of a linear dynamics model), on the basis of which linear measurements are made. It should be added that with a weak model of the actual system, the Kalman filter will not function properly.

It is assumed that this system model is driven by *Gaussian* white noise with known statistics, and the measurements are also damaged by *Gaussian* white noise with known statistics.

The complete set of models that the filter needs, consists of a system dynamics model, various measurement models of system sensors and stochastic models for model uncertainty, measurement noise and system errors and noises.

Because all Kalman filters are implemented using a digital computer, a version of the data sampling filter is used, this calibrated data filter uses a propagation update cycle. The propagation cycle assumes an estimate of the system state filter from the previous sample time and provides a new estimation of the system state in the current time based on the dynamics model.

The update cycle appears when new measurements are available and update the system status based on new measurements and the system measurement model [16].

In summary, it should be noted that testing GPS receivers for the needs of the INS/GPS system for interference of all types is possible only in laboratory conditions, thanks to the access to advanced GPS signal simulators.

A much more complex problem is the testing of INS systems, due to the limited possibilities of recreating the influence of the gravitational field.

Therefore, the tests are replaced with simulations, in which the reactions of systems in complex motion trajectories are modeled with limited precision.

Therefore, field research only becomes the final element in the assessment of this type of integrated systems. The point of reference for assessing the accuracy of the location determination in such studies are the indications of differential GPS systems [17].

The limitation of the testing capabilities of both systems is cumulative in the case of the need to conduct integrated systems research, in particular in the conditions of electromagnetic interference.

The proposed solution to this problem is to use real inertial measurements and enter false data into the filtration algorithm to simulate the situation of a successful electronic attack. In addition, this solution allows an unlimited number of interference scenarios and system evaluation in all traffic conditions.

3 Mathematical Model

3.1 Equation of the state model

The following equations contained in the following sub-chapters of this article for the purpose of developing a mathematical model of the integrated system to a large extent were based on [18], [19]. Therefore, for the purpose of the analysis, the following determinations were made: large bolded letters- mean matrices, lowercase letters- mean vectors, and normal or italic- scalar variables. In contrast, random vectors are marked in bold.

The system dynamics of the real system is described using a mathematical apparatus in a linear manner, with the differential equation of the state of the form with the following form:

$$\mathbf{x}(\mathrm{t}) = \mathbf{F}(\mathrm{t})\mathbf{x}(\mathrm{t}) + \mathbf{B}(\mathrm{t})\mathbf{u}(\mathrm{t}) + \mathbf{G}(\mathrm{t})\mathbf{w}(\mathrm{t}) \tag{1}$$

where:

$\mathbf{x}(\mathrm{t})$ = n- dimensional system state vector;

$\mathbf{F}(\mathrm{t})$ = n × n- system dynamics matrix;

$\mathbf{B}(\mathrm{t})$ = n × r- input control matrix;

$\mathbf{u}(\mathrm{t})$ = n- dimensional input state matrix;

$\mathbf{G}(\mathrm{t})$ = n × s- noise input matrix;

$\mathbf{w}(\mathrm{t})$ = s- dimensional dynamics noise vector.

The above equation (1) can also be written in the following form:

$$\begin{aligned} &\mathbf{x}(t_{i+1}) \\ &= \boldsymbol{\Phi}\left(t_{i+1,t_i}\right) \times (t_i) \\ &+ \left[\int_{t_i}^{t_{i+1}} \boldsymbol{\Phi}(t_{i+1,\tau})\mathbf{G}(\tau)\mathrm{d}\boldsymbol{\beta}(\tau)\right] \end{aligned} \tag{2}$$

where: $\boldsymbol{\beta}$- is the vector value of *Brownian* diffusion motion ***Q(t)***, and where $\boldsymbol{\Phi}(t_{i+1}, t_i)$- is the state transition matrix from time t_i to time t_{i+1}.

This state transition matrix (assuming the unchanging time matrix F) is given by:

$$\begin{aligned} \boldsymbol{\Phi}\left(t_{i+1,}t_i\right) = \boldsymbol{\Phi}(\Delta\mathrm{t}) = e^F \ where\ \Delta t \\ \equiv t_{i+1} - t_i \end{aligned} \tag{3}$$

The equivalent discrete time model for the differential equation of the form state is expressed by means of a stochastic differential equation, where:

$$\begin{aligned} \mathbf{x}(t_{i+1}) &= \boldsymbol{\Phi}(t_{i+1}, t_i)\mathbf{x}(\mathrm{t}_i) + \boldsymbol{w}_{\mathrm{d}}(\mathrm{t}_i) \\ \mathbf{w}_d(t_i) &= \int_{t_i}^{t_{i+1}} \boldsymbol{\Phi}(t_{i+1}, \tau)\mathbf{G}(\tau)d\boldsymbol{\beta}(\tau) \end{aligned} \tag{4}$$

The discretization of the dynamic time of white *Gaussian* noise ($\mathbf{w}_{\mathrm{d}}(\mathrm{t}_{\mathrm{i}})$) has the equation: $E\{\boldsymbol{w}_d(t_i)\} = \mathbf{0}$

$$\begin{aligned} &\boldsymbol{E}\{\mathrm{w}_d(t_i)\boldsymbol{w}_d^{\mathrm{T}}(t_i)\} = \boldsymbol{Q}_d(t_i) \\ &= \int_{t_i}^{t_{i+1}} \boldsymbol{\Phi}(t_{i+1}, \tau)\mathbf{G}(\tau)\mathbf{Q}(\tau)\mathbf{G}^{\mathrm{T}}(\tau)\boldsymbol{\Phi}^{\mathrm{T}}(t_{i+1}, \tau)d\tau \\ &E\{\boldsymbol{w}_d(t_i)\boldsymbol{w}_d^T(t_j)\} = 0, t_i \neq t_j \end{aligned} \tag{5}$$

3.2 Equation of measurement models

Both systems and related problems occurring in the real world, to which *Kalman* filters are usually applied, can be defined in continuous dynamics processes. Next, sensors generate measurements of sampled data, which are modeled as a linear, discrete equation, taking the form (6):

$$\mathbf{z}(t_i) = \mathbf{H}(t_i)\mathbf{x}(t_i) + \mathbf{v}(t_i) \tag{6}$$

where: $\boldsymbol{z}(t_i)$- is a modeled measurement, $\boldsymbol{H}(t_i)$- is the matrix of the measurement model, and $\boldsymbol{v}(t_i)$- is the measurement noise, with the form (7):

$$\begin{aligned} E\{\mathbf{v}(t_i)\} = 0 \\ E\{\mathbf{v}(t_i)\mathbf{v}^{\mathrm{T}}(t_j)\} = \begin{cases} \mathbf{R}(t_i) & for\ t_i = t_j \\ \mathbf{0} & for\ t_i \neq t_j \end{cases} \end{aligned} \tag{7}$$

3.3 The system of propagation and updating calculations

As previously mentioned, the discreet *Kalman* filter uses a propagation cycle to provide system estimates. The filter must have initial conditions for system states, in the form of vector (t_0) and covariance of state, with the matrix $\boldsymbol{P}(t_0)$. Once they are made available, the filter can start propagating over time to the first update cycle.

Propagation equations are as follows:

$$\begin{aligned} \mathbf{x}(t_i^-) &= \boldsymbol{\Phi}(t_i, t_{i-1})\boldsymbol{x}(t_{i-1}^+) \\ \boldsymbol{P}(t_i^-) &= \boldsymbol{\Phi}(t_i, t_{i-1})\boldsymbol{P}(t_{t-1}^+)\boldsymbol{\Phi}^{\mathrm{T}}(t_i, t_{i-1}) \\ &\quad + G_d(t_{i-1})\boldsymbol{Q}_d(t_{i-1})\boldsymbol{G}_d^{\mathrm{T}}(t_{i-1}) \end{aligned} \tag{8}$$

where: upper index "+"- represents the state of the filter and covariance estimates after the update cycle, and the upper index "-" - means the filter state before the update cycle.

When the sensor measurements become available, they update the state estimates using the following equations:

$$\begin{aligned}\mathbf{K}(t_i) = \mathbf{P}(t_i^-)\mathbf{H}^{\mathrm{T}}(t_i)[\mathbf{H}(t_i)\mathbf{P}(t_i^-)\mathbf{H}^{\mathrm{T}}(t_i) \\ + \mathbf{R}(t_i)]^{-1}\end{aligned}$$

$$\mathbf{r}(t_i) = \mathbf{z}_i - \mathbf{H}(t_i)\mathbf{x}(t_i^-) \tag{9}$$

$$\mathbf{x}(t_i^+) = \mathbf{x}(t_i^-) + \mathbf{K}(t_i)\mathbf{r}(t_i)$$

$$\mathbf{P}(t_i^+) = \mathbf{P}(t_i^-) - \mathbf{K}(t_i)\mathbf{H}(t_i)\mathbf{P}(t_i^-)$$

Matrix $\boldsymbol{K}(t_i)$- "amplification" of the Kalman filter and determines to what extent the filter is based on its own internal dynamics model, and to what extent is it based on new measurements. $\boldsymbol{K}(t_i)$ values are affected by the values set in the measurement noise matrix $\boldsymbol{R}$. The vector $\boldsymbol{r}(t_i)$- is called the residual vector and represents the difference between the actual measurement values and the predicted calculations.

The "tuning" of the filter consists in adjusting the noise power of the $\boldsymbol{Q}$ dynamics process and the covariance of measuring disturbances $\boldsymbol{R}$ for the best filter performance. The filter performance can be measured by how well it models and predicts system performance in the real world, and also on the basis of how well its $\boldsymbol{P}$ covariance matrix, which gives the estimation of the filter's own accuracy, corresponds to the actual accuracy of the filter.

It should be noted that a properly designed and well-tuned filter will have leftovers that are zero, indicating that the filter provides the best possible use of measurements.

4 Architecture of the test hardware platform

4.1 XSens MT-9B

Taking into account that the purpose of these tests is based on a real-time system, selected tests of the IMU unit of the micro-electromechanical MEMS system were carried out. The process of integration of the MEMS system and the IMU unit, used for the actual collection of data, is based on the XSens MT-9B platform, which belongs to the ISS *(Inertial Sensors Systems).*

The MT-9 test equipment was compared with another IMU, MicroStrain 3DM-G, and was chosen because it had much lower quantization and gyro drift. *XSens* is a small Dutch company that has designed the MT-9 module specifically for body tracking applications. The MT-9 module contains 9 MEMS sensors: three gyroscopes, accelerometers and magnetometers.

It has the ability to detect objects characterized by the following technical parameters: rotational speed up to 900 [°/s] and acceleration of 100 [m/s²], its options allow to receive "raw" and calibrated data, with assigned time from the internal counter.

Raw data consist of sampled measurements converted into a digital form, and the calibrated data is compensated because of misalignment and deviation of the device (both are measured at the factory). In addition, MT-9 is able to achieve output speeds up to 256 [Hz], and its power demand is low, amounting to approximately 220 [mW].

It is very small (about 3.6 cubic inches), or 58.99 [cm^3], and weighs only 35 [g]. The output interface uses the standard RS-232 serial standard.

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4.2 NovAtel Black Diamond System

To provide a reference system for comparing the MEMS system, the Black Diamond System NovAtel system (BDS) was used. The BDS system is integrated with the INS/GPS system using the *Kalman* filter, which provides 100 [Hz] of output data. The IMU modules (sensors) used in the BDS system are Honeywell HG-1700.

This system uses laser gyros, which are much more accurate than the MEMS gyroscopes based on MT-9 modules. Gyroscopes of the IMU were tested and found to reach a drift of about 0.1.

4.2.1 Measurement model

The measurement model, contained in the matrix *H*, binds measurements to filter states. The chosen model for this implementation uses the pseudo-range of the GPS minus system, which can be called the "pseudorange of INS" as a component *z*.

The pseudorange of the INS system is the distance to the satellite, calculated from the one indicated by the INS system. The measurements made in this way boil down to the fact that the results are linear with respect to measurements and a standard, linear *Kalman* filter model can be used.

Equations, presented below, describe various components of the pseudonyms of INS and GPS systems [20]:

$$\begin{aligned} \rho_{gps} &= \rho_{true} + \delta t + v \\ \rho_{ins} &= \rho_{true} + \delta_{\rho ins} \end{aligned} \tag{10}$$

The pseudorange of the GPS system is described as the true distance (ρ_{true}) plus the GPS system clock error (δt) plus the measuring noise v. The pseudorange of the INS is defined as the true distance (ρ_{true}) plus the distance error of the INS system $(\delta_{\rho ins})$.

Hence, the measurement vector z can be calculated in the following way:

$$z = \rho_{gps} - \rho_{ins} = \delta t - \delta_{\rho ins} + v \tag{11}$$

It is assumed that the pseudorange provided by the GPS receiver is a true pseudorange (ρ_{true}). The line from the indicated INS position to the GPS satellite is the pseudorange of the INS system (ρ_{ins}).

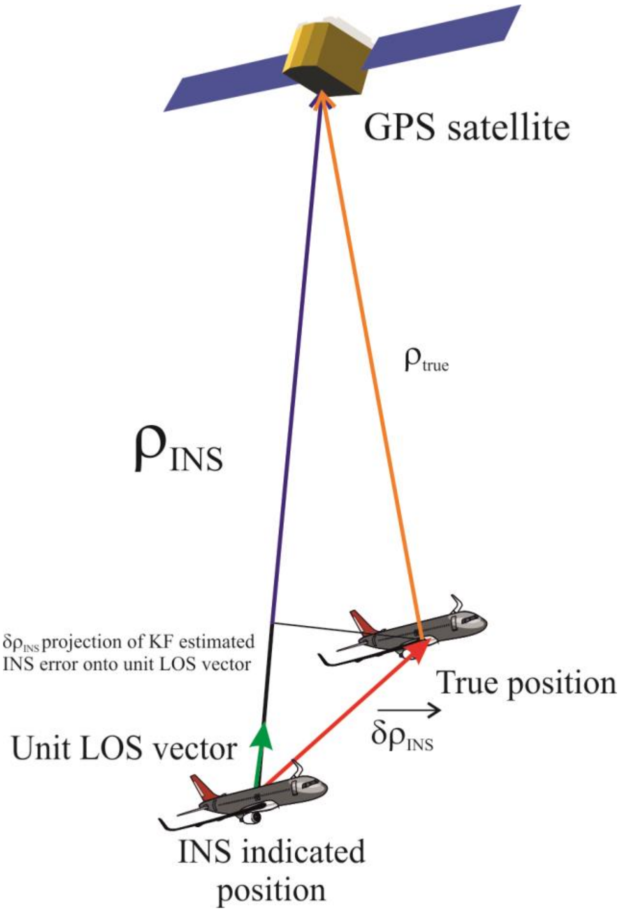


Fig. 2 Filter measurement model

The bold part of this line, i.e. the INS system range error $(\delta_{\rho ins})$, is the desired measurement (it can be positive or negative, depending on where the position indicated by the INS system is related to the real position).

4.3 Data collection

To test the structure of the system filter, the experimental data had to be collected and processed. As discussed in section 4.1, the integration in the form of IMU MEMS, which was used in this study, is the XSens module MT-9B. The Noveltel Black Diamond System was used to provide reference data giving reference points.

Ideally, the selected experimental data set used to evaluate this filter design was obtained from a device capable of highly dynamic motion. This is desirable because it not only provides a wide range of real conditions for testing the dynamic range of the filter, but also because the dynamic data provides the filter with more information about its system status, which leads to better performance.

To provide several different data sets containing different dynamics, as well as one long data set, the MATLAB script that registered the data was run by about 15 [min]. At that time, a series of right-hand wheels, left-hand and figure eight wheels, as well as a random flight period were made.

The last period included starting and stopping often and forcefully, fast turning in different directions. The platform was stopped between different sets of maneuvers and remained motionless for 13 [s] or more. The purpose of this study was to provide data with several different "starting points", because *Kalman's* filtering software required stationary data to self-initiate and self alignments.

The end result was a set of data that can be divided into different sets of maneuvers or used as a whole to provide a long-term analysis of the operation of the filter. Due to a software error in the MATLAB script, the data of the MT-9 module was not correctly saved in real time [21].

To this end, to improve this and enable the use of data, both data were examined with the MT-9 module as well as with the BDS system. It should be noted that along common axes, data obtained from accelerometers from both systems differed in obvious peaks and valleys. When an identical "peak" or valley was found in both data sets, the GPS time stamp recorded in the BDS system here it has been assigned to the data of the MT-9 module at the same point.

It should be noted that the *Kalman* filter also needs "raw" pseudo-range GPS system and satellite ephemeris data, so the data of the GPS system recorded was used in the BDS system.

This means that some of the same raw data was used as input to both the filter and the BDS (which provided reference data). Although this correlation between the filter data and the actual data is not ideal, the difference between two sets of pseudorange of one frequency delivered by different GPS receivers should be minimal. Also, the technical complexity would increase significantly when you try to register a separate, independent set of GPS system measurements for the filter.

The angular alignment calculations performed by the system are relatively simple. One of the more important requirements of the exact gyroscopic adjustment of the INS system is that the gyroscopes sense the Earth's rotation speed, which is 0.00418 degrees/sec. The gyroscopes of the MT-9 module have a noise level of 0.745 deg/s, so they can not accurately measure the speed of the Earth using a single measurement.

It should be noted that while this noise level problem can be mitigated by averaging measurements over time, the real problem is the instability of the load that interferes with the operation of the MEMS system gyros.

With an unknown deviation of the gyroscope from on to off, the velocity of the Earth can not be detected, even at averaging, to remove the noise from the device.

A typical INS system with navigation performs a "preliminary" alignment, which provides a coarse initial setting followed by a "gentle" alignment that increases the accuracy of the setting. With this system, a substantially coarse alignment is generally made [22].

During the first 5 [s] of data, the IMU must be stationary (this is done to determine the initial gyro deviation, as well as the alignment). During this time, all measurements of the accelerometer, gyroscope are recorded and magnetometer in all three axes and average values are calculated (to reduce the effects of appliance noise). In turn, because the INS system is stationary, all perceptible accelerations are caused by gravity. Thanks to this knowledge, initial tilting determination and the amount of noise can easily be calculated using medium accelerometers.

For the yaw angle, the MT-9 module magnetometers are used to detect the course relative to the magnetic field of the Earth. After determining the roll, slope and yaw angles, a direction cosine matrix DCM *(Direction Cosine Matrix)* signal is generated that links the orientation of the INS to the navigation reference system.

The average error (using four different alignment data sets) for this angular alignment method, compared to BDS data, was 0.333 degrees in the axis of rotation and 0.105 steps in the pitch axis. The yaw axis, which is the most difficult to compensate (due to the lack of gravity in this axis), had an average error of 4.62 degrees. There are separate variables in the system code that are subtracted from each gyroscope and accelerometer measurement.

These variables represent estimated instrumental errors. During the five-second stationary alignment period, the gyroscope measurements are summed up and the average value is created (one for each gyroscope). With excellent instruments, these values would be zero, because the IMU system does not rotate (except for very little terrestrial rotation).

Over time, the output positions, speed and output parameters differ from the real ones. As these errors become larger, *Kalman* filtering becomes more and more difficult to properly estimate. One of the reasons is that a large INS system error violates the key assumption of the filter measurement model (see Figure 3). To solve this problem, the INS system resets after each filtering cycle, regardless of whether it is a propagation/update state of the cycle or just a propagation cycle.

The reset occurs when the INS system begins substantially from the beginning, using the previous values corrected by the estimated errors of the *Kalman* filter as the new initial values. These filter error estimates are then reset (all other filter states remain unchanged). Initially, the INS system was to be reset each time the filter error estimates increased above certain limits, but it turned out that when the INS system was reset more often, the overall system accuracy increased.

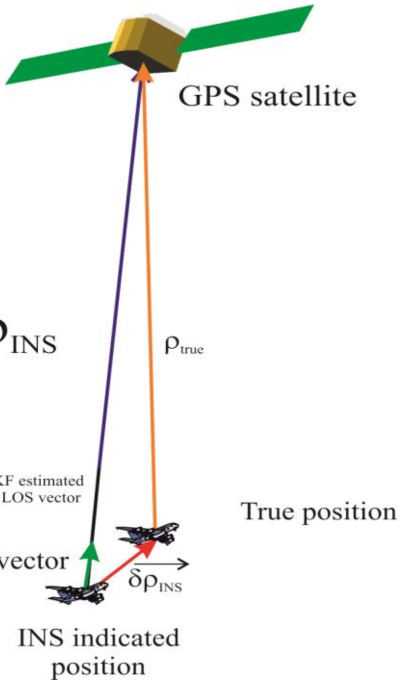


Fig. 3 The measurement model using the *Kalman* filter

5 Results of Short Term Research

The following figures (Figs. 4-7) show comparisons between BDS system data and filter output data. The BDS system indications are black lines, and the filter values are marked as green lines. The following figures (Figs. 8-10) illustrate the comparison of the filter error with the standard deviation estimates of its covariance, with an error calculated by subtracting the filter results from the results of the BDS system.

For these graphs, the error is marked in black and the standard deviations of the filter are marked in green. However, the table 1 contains a summary of the depicted data.

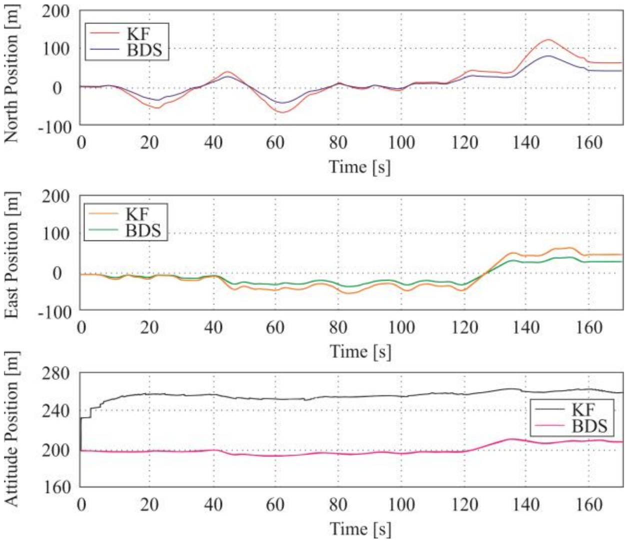


Fig. 4 Indications of the position in the axis North-South, East-West and height

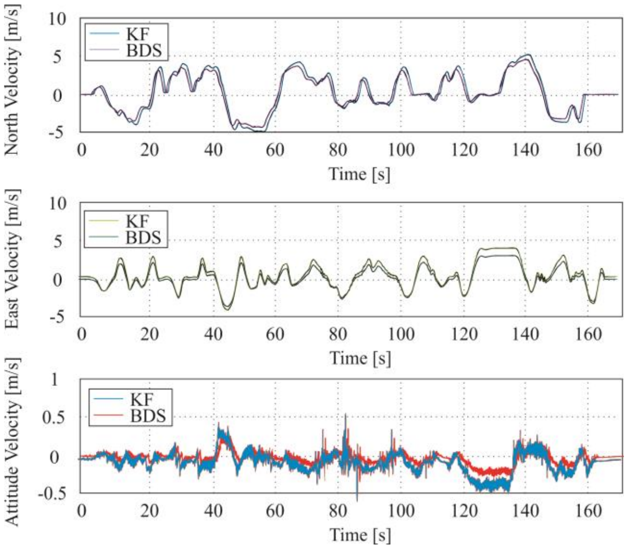


Fig. 5 Indications of the position in the North-South axis, East-West axis and the speed indication at the time of its reduction

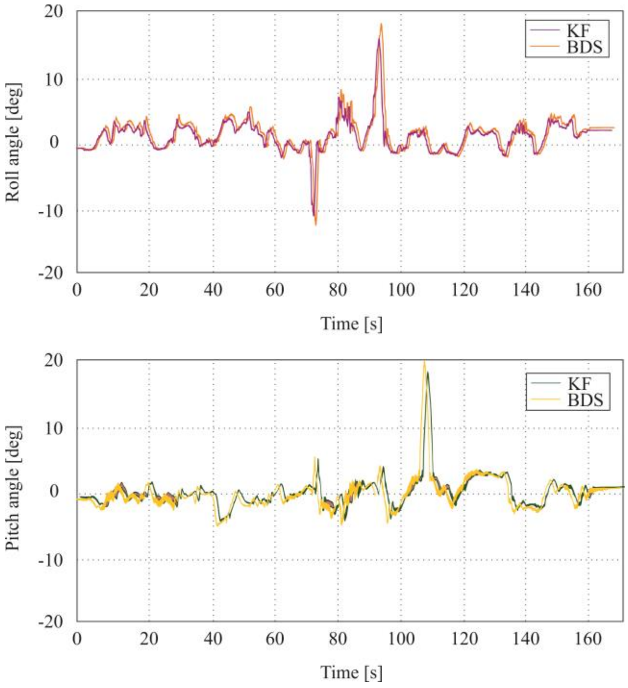


Fig. 6 The results of tilt angle measurements and slope in the study over a short period of time

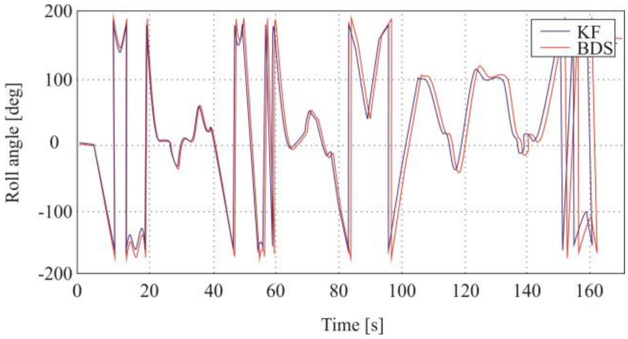
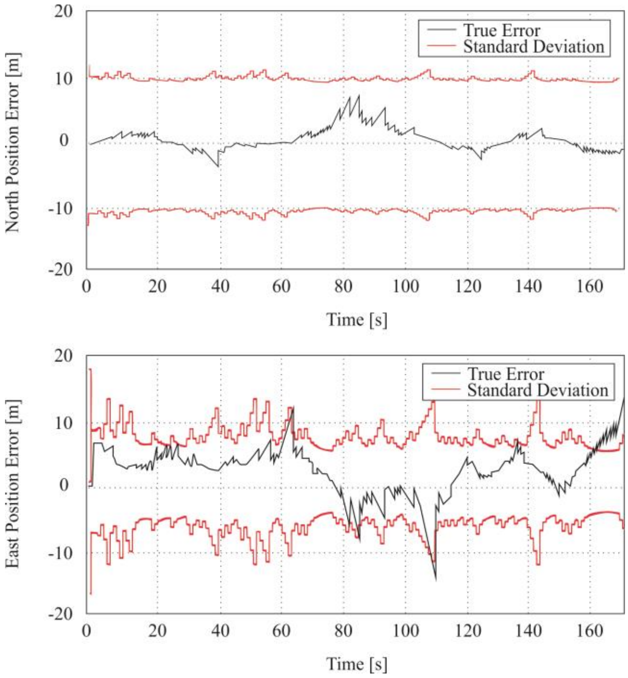


Fig. 7 The results of measurements of the deviation angle in a short period of time



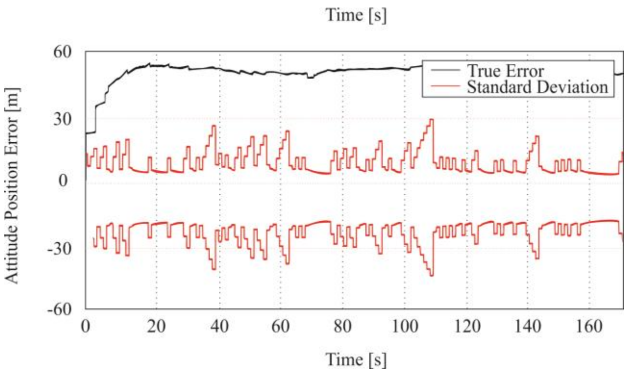


Fig. 8 Position error and standard deviation of positions in the north, east and height axis

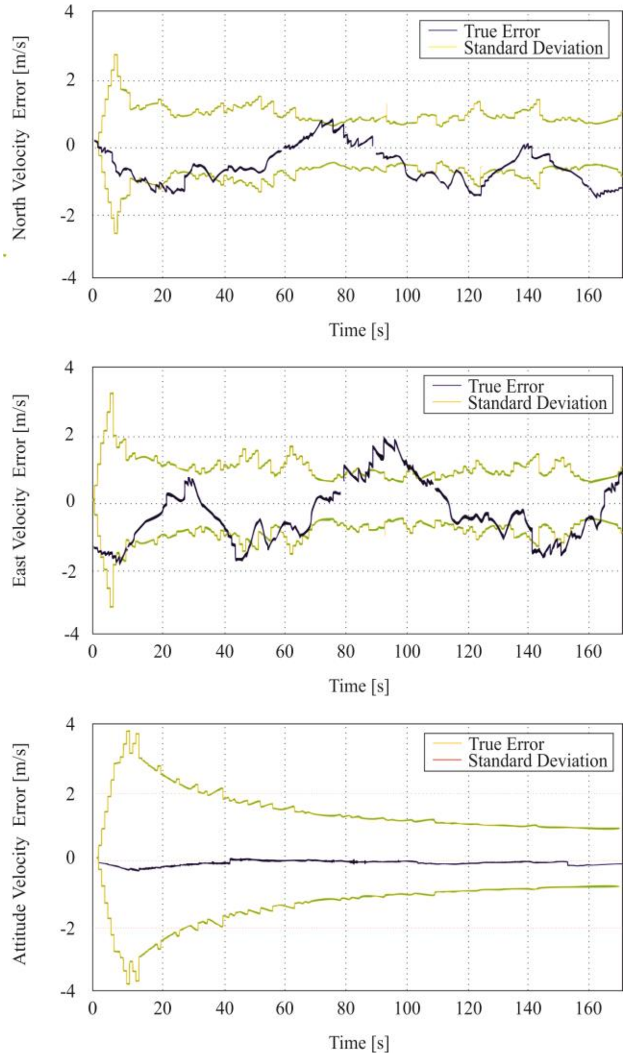


Fig. 9 Errors of indicated speeds and standard deviations in the North, East axis, at the moment of speed decrease

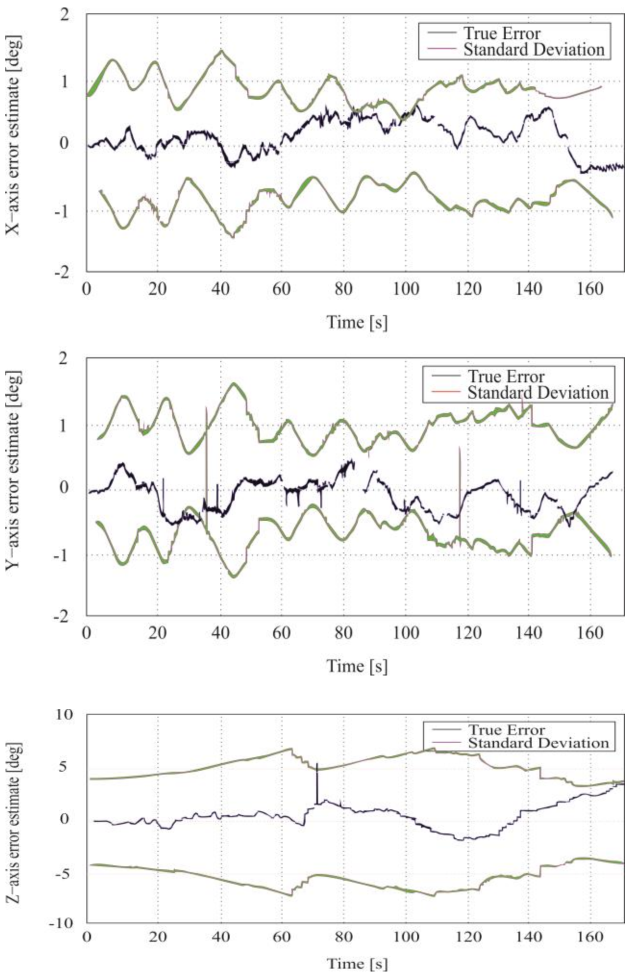


Fig. 10 Errors and standard deviation of angle measurements in X, Y, Z axes

Table 1 Comparison of "short-term" data

Filter Output	**Mean Error**	**Error Std. Dev.**	**Pet. within *la***
North Position	6.42 m	2.59 m	23.8
East Position	1.52 m	2.09 m	82.7
Altitude	34.8 m	3.19 m	0.48
North Velocity	0.132 m/s	0.662 m/s	78.8
East Velocity	0.0298 m/s	0.698 m/s	70.1
Down Velocity	-0.0721 m/s	0.285 m/s	99.2
X-tilt	0.0262 deg	0.586 deg	53.7
Y-tilt	0.110 deg	0.585 deg	54.4
Z-tilt	-3.78 deg	3.87 deg	67.4

The height error was probably caused by defective GPS system processing, the result of the system's GPS code was double checked against the output from the verified MATLAB program code (both used the same input data), and the items were the same. The altitude deviation is most likely caused by the additional processing of the GPS system.

More developed tropospheric or ionospheric correction models may also be the source of such discrepancy (the system based on the MEMS system uses the tropospheric correlation model, modified *Hopfield* model). In addition to the altitude error, the remaining results seem to be true, with most errors close to zero.

Standard filter deviations are a measure of the certainty of a filter in its results. The *Kalman* filter theory states that with a well-tuned filter, the results should be within one standard deviation from the truth (68.3 percent of the time). Most of the output filters are close to this number, with the exception of north axis errors, altitude and speed. Altitude errors have already been discussed. Mid-axis errors are very close to one standard deviation, even if most of them go beyond this limit.

The speed drop error is very small. Attempts to reduce the system dynamics noise for this state have resulted in little or no change in the covariance of the filter. Basically, with other tuning parameters remaining unchanged, the filter is secure.

This test proved that the filter performance is sufficient in a short time. Each error state was approximately constant throughout the entire data set, which could be expected in a short period of time. However, a real system performance test occurs when a longer set of data is tested.

6 Conclusions

The main conclusion that can be drawn from this study is that there are currently inertial instruments of the MEMS system, which are accurate enough to be useful in the practical, relatively cheap integration of the INS/GPS system. However, it should be noted that the proposed proposal has some reservations, namely:

1. The MT-9 module has an excellent ability in providing the right settings. Obtained results of inclination angle measurements and tilts are fairly accurate, usually within the error limits of 1 or 2 degrees, but their results for the course have much more errors (up to 35-40 [°/min]). Its ability to track the course is reduced by high levels of noise (especially in a gyroscope), which prevents him from sensing the rotational speed of the Earth.
2. MT-9 module can not operate independently for more than a minute. After 60 seconds, the position error can be up to hundreds of meters, and after this time it grows so fast that the solution quickly becomes useless. This limits its usefulness as a backup solution in the event of a GPS signal failure. However, even a 30-second operation can still be useful in the case of blocking signals by buildings or trees, providing a reasonable solution until the GPS receiver is able to recover the signal.
3. The weakness of the *Kalman* filter integration is that the filter corrects the direction error only when the system is moving. Even if the system remains stationary for less than a minute, the overall rate error continues to increase (see Figs. 9-10). During the movement, the filter is effective in correcting any existing error and then keeping the error of the course less than five degrees.

The final conclusion is that the use of closely related integration was a good choice for this system. The filter can use any number of satellites, not just a minimum of four. The system to some extent mitigates the poor performance of the MT-9, allowing the filter to continue to use GPS measurements when the loosely connected system relies entirely on the MT-9 module. The complicated system also helps to better determine INS system errors because it uses data that has not been pre-processed.

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