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DEVELOPMENT OF METHODS AND ALGORITHMS FOR IMPROVING ACCURACY OF INERTIAL-SATELLITE NAVIGATION SYSTEMS

ABSTRACT

Of the PhD thesis on specialty D074600 – «Space engineering and technologies»

The relevance of the research. Global navigation satellite systems (GNSS) play a key role in many areas in modern world, such as civil and military aviation, see and land navigation, or geomatics. GPS information is a primary source of navigation information for autonomous vehicles, as it allows the real time determination of a moving vehicle's precise position, and it has time independent accuracy.

GPS is a system that is based on a 24-satellite cluster to obtain an exact position on the Earth anywhere, at any time, and in any weather. A GPS receiver needs at least four navigation satellites information to determine the actual location of the object in three-dimensional space (x, y, z) with a less than 20-meter precision error. Furthermore, it is possible to reduce this error to less than two centimeters with five satellites minimum, using so-called differential correction mode (DGPS - Differential GPS). Nevertheless, GPS-based vehicle navigation has one major drawback: the presence of various obstacles such as trees, tunnels, high buildings, special signal jammers, can cause signal block during indefinite period of time resulting in information loss. For unmanned vehicles (our experiments were carried out using one of these cars), this situation is equivalent to a temporary vehicle guidance failure. To improve this, the integration of GPS data with an inertial navigation system (INS) is an optimal solution.

Inertial navigation systems (INS) appeared before satellite navigation systems (GNSS) and were widely used in ships and aircraft navigation, geodesy, space and rocket technology. INS determines the vehicle's position by measuring the linear acceleration and angular velocity exerted on the system in an inertial reference frame with the Inertial Measurement Unit (IMU). An IMU is a measurement system consisting of angular rate sensors and accelerometers. With IMU information and the odometry, it is possible to calculate the actual position of a vehicle from an initial location, where the accuracy of the navigation is not dependent on external signals. INS is able to calculate the location of moving objects without any additional navigation data received from other devices, but they are exposed to random errors growing over time. Such errors lead to a high deviation of the final result in determination of the object location. For this reason, in order to improve navigation results, the INS is integrated with other navigation systems in the world practice.

Integrated inertial-satellite navigation systems (INS/GPS) are the most perspective class of all existing navigation systems in the modern world. This kind of navigation systems combine the advantages and compensate shortcomings of using separate INS and GPS. The benefits of INS/GPS from conventional GNSS are: signal continuity (functioning during the period of lost GPS signal), the ability to calculate the angular orientation of an object, high frequency of obtaining navigation data. In integrated systems, it is possible to use lightweight and compact low-cost INS, constructed on the base of microelectromechanical (MEMS) sensors. The autonomous use of such INS is difficult due to the instability of the system characteristics of MEMS gyroscopes and accelerometers that lead to fast error growth while determining navigation data.

The thesis describes option of integrating INS and GPS using a special mathematical application called Kalman filtering, which allows inertial sensors error estimation by comparing GPS measurements of speed and location with the calculated INS data.

In addition to the requirements for accuracy, nowadays navigation systems have requirements for such parameters as integrity, availability and continuity of navigation support. Integrity is a measure of the probability of detecting the output performance of the system (primarily of the accuracy) of the desired limit and report on for a predetermined time interval. Availability is determined by the likelihood of a consumer receiving reliable information at a given point in time with the required accuracy. Continuity is characterized by the probability of providing the system with reliable information for a given time interval. Finally, reliability is defined as ability of a navigation system to maintain a predetermined probability of its characteristics within the required limits for a certain period of time in any area.

Ensuring specified levels of accuracy and specified quality indicators of reliability imposes special requirements on modern and advanced navigation systems for maneuverable technology. Inertial (INS) and satellite navigation systems (SNS) are one of the main modern onboard navigation systems. Inertial navigation systems have long been standard equipment on large aircraft. The aviation standard for high precision INS of civil aircraft is considered to be the accuracy corresponding to the coordinate error in 1 nautical mile per flight hour (1.8 km / h). Examples of the implementation of more accurate systems in which coordinate determination error does not exceed several hundred meters per hour of flight are known. Satellite navigation systems have been actively used in aviation applications only in the last decade and are rapidly taking place in regular composition of onboard equipment. The operating experience of GNSS has shown that, despite the many positive qualities of the GPS, they cannot satisfy all requirements set today for the quality characteristics listed above.

There are four main levels of GPS and INS integration:

- Separate Systems. In this method autonomous satellite navigation solutions of velocity and coordinates of the object are just replaced by corresponding inertial system information.

- Loosely Coupled Systems. In this method INS solutions correction problem is solved with the help of autonomous solves of speed and position of satellite navigation system

- Tightly Coupled Systems. In this integration option, the primary information of the GPS signals receiver (code pseudo-range, Doppler pseudo-velocity, phase measurements) are used as corrective measurements for the INS.

- Deep Integration. In addition to tight integration option provides feedback to the GPS correlators, that lead to the construction of a new hardware complex, the sensitive elements of which are both inertial sensors — accelerometers, gyros, angular velocity sensors, and GPS correlators.

First type of integration is currently rarely used. The second option has long become a standard, well-established way of integrating inertial and satellite navigation systems. The third option – tight integration of INS and GNSS, is a new direction that is currently just beginning to be actively worked out at the research and development stage. The last, fourth option - deep integration is the least studied and newest direction, which is the consequence of the evolution of tightly integrated complexes.

The research problem is known, many publications are devoted for it.

However, they doesn't describe the mathematical models and details of integration algorithms that are important for applications and implementations, but only the final results of the functioning of integrated systems are given. At the same time, there are practically no sources describing clear algorithmic scheme suitable for writing software. The large reason of this is that such software is either a commercial secret or intellectual property of a software developer.

According to the reasons written above, the development of algorithms and methods for improving accuracy of complex inertial-satellite navigation systems is actual scientific-technical problem in present time.

As a matter of fact, that for creating tightly-coupled and deep-integrated system we need access to internal composites of satellite navigation receivers, the loosely-coupled method was chosen for INS/GPS, INS/Odometry and INS/GPS/Odometry integrations using Kalman filter.

The purpose of the thesis is: development of fully autonomous high-precision low-cost inertial-satellite navigation system that keep functioning while satellite navigation information is out of availability, and research methods and algorithms for improving it's accuracy.

The objectives of the thesis are:

- Inertial sensor errors compensating methods;
- Development of mathematical model of INS;
- Vehicles coordinate determination using odometry;
- Development of mathematical-software application for hybrid INS/Odometry and INS/GPS/Odometry systems.

The object of the study is the system consisting GNSS receiver, odometer, low-cost three axis accelerometer and gyro.

Subjects of the research are integrating algorithms of inertial and satellite navigation systems, INS accuracy estimation algorithms.

Methods employed in the research. For studies methods of mathematical analysis, mathematical statistics, linear algebra and multidimensional geometry, theory of optimal filtration, applied programming were employed. For the formulation of the problem, mathematical apparatus of the theory of rigid body motion, the mathematical apparatus of the theory of inertial and satellite navigation, as well as computer modeling were utilized.

Statements for defense. The following issues have been addressed by the results of the study:

- Mathematical-software application of six-position (SPM) and nine-position (MPM) inertial sensor calibration methods for eliminating various types of INS errors have been developed and tested;
- Mathematical-software complex of coordinate determination using INS consisting three axis accelerometer and gyroscope has been developed;
- Mathematical-software model of vehicle localization using odometry has been developed;
- Algorithms of loosely-coupled integration of navigational information from various sensors: INS/Odometry and INS/GPS/Odometry using Kalman filter have been developed;
- All developed methods and algorithms were tested on the base of experimental measurements carried out using real sensors installed on real unmanned vehicles. Obtained results have been analyzed.

The validity and reliability of the research and carried out results is proved by the correctness of the use of methods and algorithms of control theory, as well as a sufficient number of numerical simulation and obtained consistent results, which are consistent with known data published in the open press. The results were confirmed by experimental studies conducted by the author.

Theoretical and practical significance of the research.

From a theoretical point of view, scientific and methodological support has been developed for creating hybrid navigation systems - a set of methods and techniques, the order of their application, interpretation and obtaining results.

The developed hybrid system is applicable in various areas of military and civil navigation, such as motion monitoring of various mobile objects, high-precision navigation of ground, shipping, and aerospace vehicles, navigation of vehicles in the absence of GNSS signals, missile guidance, etc. Also, such systems together with object recognition (computer vision) and laser ranging systems are one of the main onboard systems for creating unmanned vehicles, which have recently been actively developed by such large companies as Google, Yandex, Tesla, etc.

The author's personal contribution is that all the results shown in the thesis have been obtained by the author or with her direct participation. The coauthors and scientific advisors participated only in the problem definition and discussion of the results obtained.

Approbation (testing) of the results of the study.

The obtained results were presented: 2 articles in Materials of the LXX International Scientific and Practical Conference "Technical sciences – from theory to practice" (Novosibirsk, 2017, № 5(65)); 1 article in International Conference "Satpayev readings - 2014: "The role and place of young scientists in the implementation of the strategy of Kazakhstan-2050". The main results on the topic of the thesis are presented in 14 published works, 1 article is in the Scopus database, 3 articles are from the list recommended by CCSON MES RK and 3 reports at international scientific and practical conferences.

Structure and the scope of work.

The thesis consists of an introduction, three sections, conclusion, a list of sources used and an appendix.

Chapter 1, describes different positioning systems and their operating concepts, and summarizes their advantages and disadvantages for application in a hybrid system. The equations of the inertial navigation system are presented, and on their basis, the error equations are derived. A new algorithmic scheme for vehicle's position and orientation determination using information obtained from a three axis accelerometer and gyroscope using transition matrices between different reference systems and integration methods is presented. Also, it is suggested the use of odometry to improve the accuracy of inertial navigation. Models of determining the location and course of the vehicle on the plane according to data obtained from odometers located on two wheels of the vehicle, and restrictions for this model are shown. Odometric equations for two-wheeled and four-wheeled vehicle models are presented.

Chapter 2 discusses various techniques of increasing accuracy of INS/GPS. It provides general information about the Kalman filtering, an overview of the types of INS/GPS integration and the method of loosely coupled integration is chosen. An algorithm for a hybrid INS/Odometry system is proposed for cases of GNSS information loss as a result of various interference effects. The model of the implemented Kalman filter and its parameters are characterized. The technique of time synchronization between GPS and inertial sensors data are explained. Some aspects, like initialization of used filters, setting their parameters are also considered. The types of system errors of the inertial navigation module are described in detail, a six-position and nine-position calibration methods to compensate the most significant ones — bias errors, scale factors, and non-orthogonality factors of accelerometers and gyros are developed and tested using cheap MEMS sensors.

The third chapter describes the process, results and their analysis of the carried out experimental tests.

First of all, primary processing was performed for each sensor data: the accuracy of the GPS information was determined, the INS system errors such as bias errors, scale factor and non-orthogonality factors were compensated by static calibration methods. Then, the results of the INS/Odometry, INS/GPS/Odometry integration were presented, and their errors relative to the reference trajectory were analyzed. The experiments were carried out using the CyBus intellectual car of the INRIA research center (Paris-Roquecourt, France) as well as databases obtained from the AnnieWay automated vehicle sensors from the KITTI project (Karlsruhe, Germany). The software was implemented using the Matlab and Simulink packages.

The conclusion section presents the findings of the study, and the recomendation for further work.

Appendix A is a very important section that describes the reference system and transition matrices between them, which were used in the inertial navigation mechanization equations and algorithm for connection between inertial and satellite navigation systems.