MEMS-based Inertial Navigation: Expectations and Reality

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The new book by Professor Oleg S. Salychev, head of TeKnol Ltd. company, is dedicated to the latest achievements in the field of MEMS-based inertial navigation systems made by the team of engineers leaded by the author. The book is focused on MEMS-based navigation systems, which can be used in integrated mode with different external sources of navigation data, as well as in pure inertial mode, which is unexpected for such kind of navigation systems. Great scientific and research experience of TeKnol Ltd. is implemented in wide spectrum of MEMS-based inertial systems, which are described in details in the present book. The book is intended to engineers and postgraduate students, practically involved in inertial instrumentation development.

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To my granddaughter Anfisa

Introduction

Seven years passed after my previous book ("Applied Inertial Navigation: Problems and Solutions") was published. That time, the MEMS based systems were already widely applied in different applications, mainly for motion sensing and attitude reference. After short period of time integrated MEMS systems became available for navigation (though with the aid of other sensors), but the related expectations were much higher. The technology boom promised the further accuracy growing up and applications field enlarging up to standalone MEMS based navigation devices. The analytics predicted for MEMS technology a spectacular future during the next decade. This feature comprised not only market growth due to more applications get available, but performance enhancement (and consequent more market growth, which is the essential at the end).

The true is, the MEMS-contained systems entered the consumer products with automation entering our life. The products like robots, unmanned systems of all kinds, vehicular motion sensors became now the frequent news headliners. But the true also is, that most of these technical solutions are from 1990-s and the progress of 2000-s mainly concerns the number of applications rather than being produced by the new quality of MEMS sensors. Meantime, the awaited (and demanded) dramatic jump in accuracy seems not to arrive. The manufacturers improved interfaces, data exchange rates, design and other appearance-related issues. But the most expected performance improvement still did not happen at the level of sensors specification. The 0.1–0.5 deg/h drift rate is not achieved for MEMS angular rate sensor. Does it mean that the MEMS-based navigation and attitude reference systems will stay at the grade of low accuracy range?

Our answer is no. And this book says, why we think so.

In the retrospective view of our more than 15-years experience of MEMS-related hardware and software development, the first and the most obvious thing we learned about MEMS was the fact, that classical "Schuler-tuned" algorithm of strapdown inertial navigation system was not working. And it never worked, so far. In order to provide the reasonable accuracy for such kind of the unit the error damping procedure has to be used. In case when external navigation information is available, the different kind of error damping procedures, which are not disturbed by motion parameters, can be applied. Much more problematic is the case, when the external navigation information is not available. Here the different self-damping procedures have to be implemented. But in principle all of them are disturbed by the nominal motion parameters such as accelerations. It seems reasonable to use the different calculated platforms (implementations of the navigation frame) which are adjusted to the particular carrier motion. Each platform has its own damping control law and as a result has different error frequency dominated behaviour. The master filter combines the different navigation platform solutions in order to provide the optimal one for the different motion modes. Such approach is called the multiplatform navigation solution. Using the suggested approach the line of different MEMS-based inertial systems has been developed.

In this book the experience in system design is considered in details. The more promising is the development of MEMS-based system, which is able to provide the reasonable position (1–2 n. m.) for the long time of GNSS gap (1 hour and more). The book content is dedicated to people, who were practically involved in such project: researchers, engineers and scientists.

I would like to express my gratitude to the staff of TeKnol Ltd. Company, namely I. Shakhov, V. Tereshkov, D. Pazychev for the long time productive joint work and also to V. Pisarev and A. Levchenkov for their help in book publication and effective project management. I also want to thank M. Ilina for text editing and inspiration in working on this book.

Chapter 1

Coordinate Frames

In surveying and navigation positioning the final output required by a client usually includes the coordinates of a point, namely latitude, longitude and height and their accuracies. The measurements sensed by an Inertial Navigation System (INS) are three orthogonal components of the body rotation rates and three accelerations in a coordinate frame, which is not directly related to any geodetic curvilinear coordinate frame. These measurements have to be analytically integrated and transformed through several coordinate frames, which yields changes in the ellipsoidal coordinates.

1.1 Inertial Frame

According to the Newtonian definition, an inertial frame is a frame, which does not rotate or accelerate. Such a frame is easy to define in theory, but it is almost impossible to implement in practice. The best approximation of the truly inertial frame would be one that is inertial with respect to the distant stars. One approximation of such is a frame, used in surveying applications, which is a right ascension system. The right ascension system as given in a catalogue precesses and nutates at the rate of less than $3.6 \cdot 10^{-7}$ arcsec/s, which is well bellow the noise level of inertial sensors in present iner-

Chapter 2

Principles of Inertial Navigation

2.1 General Navigation Equation

The main idea of the inertial navigation is based on the acceleration integrations. A device, which can measure vehicle acceleration, is called an accelerometer. First integration of the vehicle acceleration provides velocity. Second integration gives vehicle position increments with respect to an initial point. For the determination of the navigation parameters (velocity, position, attitude) in a certain navigation frame, the acceleration projections on that frame have to be provided. In order to match sensitive axes of accelerometers with a certain navigation coordinate frame, different types of gyroscopes are used. There are two approaches for the navigation frame simulations in the inertial system technique. First one deals with the physical implementation of the navigation frame using a three-axial gyro-stabilized platform with three orthogonally placed accelerometers. Such type of a system is called platform or gimbaled INS. The second one, called strapdown INS (SINS) provides the analytical image of the navigation frame in onboard computer, using measurements from accelerometers and rate gyros installed directly on a vehicle body.

Chapter 3

Alternative Approach to the Inertial Navigation

3.1 Principle of Multiplatform Navigation

As it was mentioned in section 2.6 the traditional Schuler tuned solution is universal but not optimal for all possible carrier motion modes.

Indeed for the relatively smooth flight the different self damped approaches can provide much more accurate results in comparison with traditional one. But in the same time in case of high maneuvers the self damping leads to the large disturbance of platform leveling. Assume that using the same raw data from the sensors the different calculated platforms with the different control laws can be created simultaneously. Each calculated platform implements its own navigation solution, which is based on the particular control procedure. Moreover, each solution is adopted for the certain motion mode and the global system output has to combine the particular solutions in order to create the final one, which is acceptable for all possible motion modes. The above approach can be called multiplatform navigation system. Here each platform

Chapter 4

Application of Multiplatform Approach to the Low Cost INS

4.1 Implementation of Traditional Approach to Low Cost INS

The low cost MEMS sensors (accelerometers and rate gyros) are now being manufactured by different world companies such as Analog Devices, Silicon Sensing Systems, Systron Donner and so on [3]. The typical performance of such gyros and accelerometers is shown in Table 4.1.

Table 4.1

Performance	**Gyro channels**	**Accelerometer channels**
Range	150…300 deg/s	5…10 g
Run to run bias	1 deg/s	10 mg
In run bias stability	0.1…0.01 deg/s	3…5 mg
Resolution	8…15 deg/h	$1 \cdot 10^{-4}$ g

The application of low cost INS can not be used in pure inertial mode because of huge output errors. It is a reason of the integration of the above unit with GNSS. The traditional approach to the low

Chapter 5

Multiplatform Approach with the Application to Medium Accuracy INS

5.1 Self-damping of Inertial Errors by Current Velocity or Acceleration

The medium accuracy MEMS-based IMU has typical specification shown in Table 5.1.

Table 5.1

Characteristics	Gyro channels	Accelerometer channels
Run-to-run bias	0.01...0.03 deg/s	2 mg
In run bias stability	0.5...2 deg/h	0.2...0.5 mg

Such type of hardware was never used for the case of long term autonomous navigation [3].

The reason of such deduction is based on the fact, that in traditional approach such value of gyro bias stability corresponds to coordinate errors of 100...200 km per hour, which are unreasonable to use in practical application.

Let's consider the self-damping procedure for such kind of IMU. The self damping procedure based on inertial acceleration of the

Chapter 6

MEMS-based Inertial System Applications

In this chapter the different applications of MEMS-based inertial navigation system will be considered.

6.1 Portable Glass Cockpit System

6.1.1 System Functionality

The idea of Portable Glass Cockpit System (PGC-A) design is to bring the functionality of a modern glass-cockpit type avionics into a cockpit of any aircraft without its modernization.

PGC-A is a complete flight and navigation instrumentation system, which is portable and fully independent from onboard systems. It includes a compact GPS-aided inertial navigation system based on MEMS sensors, GPS receiver and ruggedized tablet computer with 10,4” LCD screen as an indicator (see Fig. 6.1). The system has the functions of Electronic Flight Instrumentation System (EFIS), Flight Director (FD), Terrain Awareness Warning System (TAWS), Flight Management System (FMS), and Electronic Flight Bag (EFB).

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