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REVIEW OF THE MODERN NAVIGATION SYSTEMS AND FUTURE TRENDS OF THEIR DEVELOPMENT

Review of the modern navigation systems and their sensors is carried out. The future trends of the modern navigation systems development are considered.

Виконано огляд сучасних навігаційних систем та їх датчиків. Розглянуто перспективи розвитку таких систем.

Introduction

Navigation and orientation of modern moving objects are ones of the most important areas of science and technique. So, review of the modern navigation systems and sensors and future trends of their development is of great importance for the domestic industry. Such study will be useful for creation of the new perspective navigation systems. The most widespread modern navigation systems are the inertial navigation ones. In its turn, such systems are divided into gimbaled inertial navigation systems, strapdown inertial navigation systems, attitude and heading reference systems. In such review it is necessary also to consider the basic sensors of the inertial navigation systems, namely, the gyros and accelerometers.

The navigation systems

Litton-92 systems are one of the most popular inertial navigation systems [1]. They include inertial navigation unit (INU) and GPS module. The INU consists of three ring laser gyros and three accelerometers. Each ring laser gyro is a single-axis sensor constructed of glass-ceramic. It uses three mirrors, one curved and two flat to create a laser resonator. The GPS module consists of an embedded 5th channel GPS receiver. The INU may use three types of inertial alignment: ground, stored heading and airborne. It may operate in three navigational modes such as pure inertial, GPS only, and blended GPS/INS. The systems may be used in attitude reference mode. In this case, the system navigation capability is lost but the inertial navigation unit is capable of providing outputs of pitch, roll and heading systems.

The KN-4073 air navigator produced by Kearfott Guidance and Navigation Corporation is successfully used in both manned and unmanned aircraft [2]. It is able to work in various modes of alignment and initialization including ground, shipboard and air. Aircraft equipped with such navigator has been implemented successful landing and taking off from a ship at sea.

The navigator includes a T16B monolithic ring laser gyro inertial measuring unit and GPS receiver. This lightweight navigator (8 lb) provides positional accuracy inside 2 feet. Kearfott's high accuracy inertial navigation system SKN-2443 includes the inertial navigation unit. Navigational data are measured with such inertial sensors as a vertical accelerometer, two horizontal accelerometers and two-axis GYROFLEX gyroscopes. The sensing elements are mounted at gimbaled gyro-stabilized inertial platform. The inertial navigation unit weights 33 lbs. The system provides pitch, roll and heading information in both analog and digital form. It is capable of ground or in-air alignment. Kearfott's KN-6054 based on monolithic ring laser technology represents the marine inertial navigation system.

Northon Gruman corporation producing the LTN-92 laser gyro inertial navigation system uses three ring laser gyros, force rebalanced accelerometers and three high-speed digital microprocessors to provide an advanced technology and all-attitude worldwide navigation. Such systems are used on many transport and commercial aircraft including B747, DC-10 and L-1011.

The MK 39 MOD 3A ring laser gyro inertial navigator [3] provides both high accuracy geographic position information, with or without GPS, and precise attitude and heading data. Such system is produced by Sperry Marine.

A wide range of inertial navigation systems based on MEMS and FOG technologies is offered by Crossbow. High performance, reliability and ease of use and exploitation are the design features of such systems. Most of Crossbow’s inertial navigation systems are autonomous, but some systems may be corrected by means of GPS or Air Data Systems.

The attitude and heading reference systems

Now one of trends of navigation system development is creation of the so-called Attitude and Heading Reference System (AHRS) that is systems of determination of angular orientation and course of moving objects.

The main purpose of such systems development is change of the traditional mechanical gyros with less cost and complexity but more accurate and reliable sensors.

The highly reliable Attitude Heading Reference System (AHRS) KN-4071 [2] uses the patented monolithic ring laser gyro and a triad of Kearfott force rebalanced accelerometers as the inertial reference unit. The system provides analog outputs of heading and attitude for cockpit and flight director. The system provides improved accuracy of both attitude and heading over standard electromechanical AHRS by use of advanced ring laser gyro gyros, accelerometers and the self contained GPS card. The most popular AHRS producers are Crossbow Technology, Litef GmbH, Sagem Avionics, Watson Industries, Xsens Technologies.

The Perm Scientific-Production Device-Building Company produces AHRS ICV-705-b, ICV-802, ICV-802M [4] consisting of the gyro-stabilized platform, sensors and electronic devices and the strapdown AHRS SSCV-85, SSCV-2V. Most of such systems provides determination of the gyroscopic course, pitch and roll angles, components of the absolute acceleration along the reference frame axes. The inertial informational course and vertical systems C-050, C-060, C-061 produced by this company may be used at high maneuvering aircraft, in particular, MiG-29, SU-27, SU-30, helicopter Ka-50. The accurate course system is assigned for the passenger (Tu-154M) and transport (An-22, Il-76, Il-78) aircraft. This company is specialized in development of gyro compasses for the sea and river craft, which were created on the basis of the aviation technologies. The gyro compass “Gyuys”, “Gyuys-M” of the extended precision, gyro course detector GKU-5, marine integrated small-size navigation system “Kama”, gyro compass “Scan-2000” produced together with Danish firm Scan Steering, gyro compass “Meridian” developed together with the English firm “SGB”, the most miniature gyro compass PGM-C-009 belong to such devices. The dynamically tuned gyro is the heart of such devices.

The most widespread AHRS developed by Crossbow are AHRS400, AHRS500GA, AHRS10G. These systems carry out functions of the gyro vertical and heading gyro providing measurement of roll, pitch, heading angles.

The basic sensors of these systems are the solid-state MEMS. Such systems provide measurement of angular rates and linear acceleration along axes of the reference frame too. Comparative characteristics of Crossbow’s AHRS [5] are represented in the tab. 1.

As example of the marine AHRS may be considered the Anschütz marine inertial navigation system [6], which represents strapdown AHRS based on the RLG technology. Absence of gimbals, bearings, rotating masses ensures long lifetime and low life cycle cost. The Honeywell GG1342 is used as sensor of such system due to its high dynamic range and high performance.

The navigation gyro sensors

The ring laser gyroscopes (RLG), fiber optic gyroscopes (FOG) and micro-electro-mechanical systems (MEMS) are often used in the modern inertial navigation systems. The RLGs have excellent scale-factor stability and linearity, high sensitivity to acceleration, digital output, high stability and repeatibility. The RLG’s performance is very repeatable under temperature variations. FOGs were developed as a lower cost alternative to RLGs. But now [7] FOGs begin to match RLGs in performance and cost. The most important advantages of FOGs are absence of rotating mechanical parts that provides instrument long life cycle, wide measuring range and high precision of scale coefficient. There are the open and the closed loop FOGs.

The major advantage of the closed loop FOG is the high linearity of the scale factor and its insensitiveness against environment, especially against vibration. MEMS technology provides some advantages such as reduction in size, cost, power and design flexibility. But MEMS performances need improvement. And to achieve the suitable performance for MEMS gyros is more difficult than for MEMS accelerometers.

The most famous providers of the laser inertial systems are Honeywell and Litton. A laser gyroscope system built by Honeywell is used on the Boeing 757 and 767, the new generation of commercial transports. The European A310 Airbus uses a laser gyro unit built by Litton. [8]. Kearfott Guidance and Navigation Corporation [2] produces monolitic ring laser gyro used in the inertial navigation systems for various applications. The LTN-101E produced by Litton is the world’s first commercially certified navigation-grade fiber optic inertial sensor. It is in development for certification on the Airbus family of aircraft including the A380.

Crossbow offers a wide range of inertial products based on MEMS and FOG technologies.

High performance, reliability and ease of use are primary design features of this producer. The Crossbow VG700AB fiber optic gyro stability combines third generation high performance fiber optic gyros with the latest silicon MEMS accelerometer technology to provide functions of highly accurate vertical gyro and inertial acceleration measuring unit. The system consists of three fiber optical gyros and three silicon accelerometers. Crossbow developed also the solid-state vertical gyro VG400. This gyro may be used for unmanned aircraft control and platform stabilization.

In Russia the FOGs are produced by scientific-research company "Fizoptika". These FOGs have the bias variation from 0,5 (VG951) to 50 degrees per second. For VG951 the scale coefficient stability is 0,1 % for the constant temperature. Such devices may not be used in autonomous systems but may be applied in the integrated systems. The MEMS's gyros and systems on their basis in Russia are created by "Girooptika". This enterprise developed strapdown inertial navigation systems SINS-M and SINS-K [9] providing measurement of components of absolute angular rate and linear acceleration. These systems have the following characteristics: range of measured angular rates – 360 ^{o}/c; range of measured linear accelerations – 75g; random component of the gyro zero drift – 5 ^{o}/c; random component of the accelerometer zero drift – 0,3 mg; nonstability of the gyro scale factor ≤ 0,5%; nonstability of the accelerometer scale factor ≤ 0,3%. One of the most important problems of the strapdown inertial system alignment, namely, azimuth determination is solved based on measurement of the horizontal Earth angular rate by means of appropriate sensor and software. It is possible to believe, that this enterprise solved the basic problems of MEMS systems and sensors design and technology. And now it is necessary to improve accuracy of such systems and sensors and to provide possibility of their use in navigation.

Comparison of RLG and FOG characteristics is shown in the tab. 2 [10].

As may be seen from the table, the MEMS sensors are smaller, lower power and also less accurate. So, in future after achievement of the appropriate accuracy, the MEMS sensors will be widespread in the navigation systems.

One of the new gyro technology products is the Coriolis vibrating gyro, which represents the solid-state angular rate sensor without rotating parts. Such gyro has the higher reliability, life cycle and ratio accuracy/cost in comparison with another gyro types including RLGs and FOGs.

The navigation accelerometers

The MOD VII series of improved miniaturized accelerometers is a group of squeeze-film-gas-damped force rebalanced accelerometers (K120A030) [2] having characteristics meeting the requirements of highly accurate analog and digital applications. The basic unit is a pendulous torquer-restrained device possessing a useful dynamic measurement range from less than $1{\cdot}10^{-6}g$'s to over 60 g's. This unit provides a significant improvement in performance to cost ratio and performance to size ratio. Such accelerometers may be used in high accuracy strapdown inertial navigation systems.

Now, the accelerometer triad assembly becomes popular. Kearfott's triad assembly consists of three unsealed MOD VIIA accelerometers mounted on a support structure forming an orthogonal triad of sensors. The most famous accelerometers produced by Russia companies are digital accelerometers AD-1, electrostatic accelerometer of the compensation type EAC-1 and pendulous correction accelerometers A-15, A-16, A-17. Characteristics of such accelerometers [4] are shown in the tab. 3.

Development of the MEMS accelerometers in Russia is carried out by "Girooptika". The comparative estimation of parameters of Russian (7PUS-20(2), 7PSK(U)-360) and American (ADXL311, ADXRS300) accelerometers [9] is represented in the tab. 4.

Research methodology

The best instrument for the inertial navigation systems and their sensors research is Matlab software due to its computing capabilities, developed built-in library of functions, convenient graphical interface. It is mostly expedient to use for these purposes Simulink and Control Toolbox. The Control Toolbox provides creation, analysis and synthesis of control and navigation contours due to great number of special functions providing research of the complex engineering systems and their optimal design. The possibility of robust systems creation which is provided by this package is of great interest. But Control Toolbox may be used for the linear stationary systems only while all real systems have some linearities. From this point of view, the best instrument for creation of the models close to the real systems is Simulink.

Table 1

Characteristics of the most widespread AHRS

Parameters	AHRS420	AHRS500	AHRS510	AHRS400
Accuracy of angular position (roll, pitch), degree	<2	±2,5	±2,5	±2,5
Heading accuracy, degree	<3	±2	±2	±4
Measurement of accelerations, g	±4	–	–	±4
Dimensions, cm	7.62×9.53×7.2	11.84×11.51×12.35	11.84×11.51×12.35	7.62×9.53×10.42
Mass, kg	<0.58	1.6	1.36	<0.77

Table 2

Comparative analysis of RLG and FOG characteristics

Parameters	RLG (HG1700)	MEMS (Crista)
Dimensions, cu in	33	1,6
Weight, oz	32	0,7
Power, W	8	0,7
Operating range, $\pm^{o}$/s	1000	300
Scale factor accuracy (1σ), ppm	150	25000
Bias (1σ), ^{o}/hour	2	500
Axis alignment stability (1σ), μ rad	500	3000
Output noise (1σ), μ rad	80	80

Table 3

Characteristics of the accelerometers produced by Russia companies

Characteristics	AD-1	EAC-1	A-15	A-16	A-17
Measuring range, g	40	±10	20	35	10
Slope of curve	10,5 kHz/g	2,0 V/g	1,0-1,4 mA/g	0,9-1,3 mA/g	1,0-1,6 mA/g
Working temperature range, ^{o}C	-60…+80	–	-60…+80	-60…+80	-60…+80
Supply voltage, V	5	±15	±15	±15	±15
Overall dimensions, mm	80×30×12	24×24×8	24×20	24×20	24×20
Mass, g	50	20	≤40	≤40	≤40

Table 4

Comparative estimation of the MEMS accelerometers

Parameters	Accelerometers		Gyro	
	7PUS-20(2)	ADXL311	7PSK(U)-360	ADXRS300
Measuring range	±20*g*	±2*g*	±360 ^{o}	±300 ^{o}
Sensitivity, mg	0,6	2,0	–	–
Nonlinearity of the scale factor	0,1	0,2	0,0013	0,2
Spectral density of random component of the zero drift, mg	0,1	0,3	0,5	0,2

Trends of navigation systems development

There are two basic types of inertial navigation systems: strapdown and gimbaled. Now, the strapdown systems are the most widespread due to such advantages as small mass and dimensions, high reliability, less power consumption, less cost, ease of repair and exploitation. But creation of strapdown inertial navigation system is connected with serious technical difficulties such as development of gyros and accelerometers providing required accuracy in the wider measuring range and harder exploitation conditions, necessity of complex algorithms of coordinate transformation, initial alignment and so on. Therefore development of the strapdown inertial navigation systems is carried out together with improvement of the gimbaled inertial navigation systems. Now, it is possible to say about definite progress in creation of the gyrostabilized platform namely accuracy increase and reliability growth with decrease of mass and dimensions and ease of exploitation. The gimbaled inertial navigation systems are more stable to noise action due to mounting of the gyros and accelerometers at the platform. Now, the gimbaled inertial navigation systems are mostly applied for the marine moving objects.

FOGs and MEMS accelerometers are today used in the inertial strapdown systems for medium accuracy and expanding into high performance strapdown inertial navigation systems in competition with RLGs. The MEMs gyros are expanding to the medium accuracy ranges. Now high accuracy is provided with the RLGs. The FOGs have the moderate accuracy range from 0,01°/h to 30°/h. The MEMS gyros provide only low accuracy requirements [7]. So, one of the modern trends of the inertial navigation system sensors development is improvement of the MEMS gyros accuracy.

One of the main problems of the inertial navigation systems is GPS/INS integration. Use of GPS receiver is the strong instrument for navigation information obtaining. But use of GPS requires to see at least four satellites to achieve full precision. So, use for navigation GPS only may result in unreliability of data or complete loss of data. This problem may be solved by integration of the inertial navigation system with GPS. Such integration system allows to get continuous and reliable navigation information. Characteristics of INS, GPS and INS/GPS systems are shown in the tab. 5 [11].

Table 5

Characteristics of INS, GPS and INS/GPS systems

INS	GPS	INS/GPS
High position and velocity accuracy over short term	High position and velocity accuracy over long term	High position and velocity accuracy
Accurate attitude information	Noisy attitude information	Precise attitude determination
Accuracy decreasing with time	Uniform accuracy, independent of time	High accuracy
High measurement output rate	Low measurement output rate	Navigational output during GPS signal outages
Autonomous	Nonautonomous	Correction possibility
No signal outages	Cycle slip and loss of lock	Cycle slip detection and correction
Affected by gravity	Not sensitive to gravity	Gravity vector determination

Conclusion

The review of production state of the modern navigation systems and their sensors is carried out. The future trends of the modern inertial navigation systems development are considered.

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