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ABSTRACTS

Inertial Units on Micromechanical Sensors. Development and Test Results

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Abstract

A micromechanical gyroscope (MMG) with a disc-shaped inertial mass has been developed in the CSRI Elektropribor jointly with TRONIC'S Microsystems (France) since 2001. The key achievements of the first three years were as follows: elaboration of the technique for manufacturing MMG micromechanical silicon sensor, sealed in a high-vacuumed ceramic case, and development of special breadboard electronics, which provided experimental verification of the sensor serviceability and its conformance to the design accuracy. In the recent years the designers have focused on elaboration of both electrical and mechanical parts of MMG, and creation of an MMG-based Inertial Measurement Unit (IMU) and an Integrated (inertial/satellite) Attitude and Navigation System (IANS).

The MMG of performance class 0.1 deg/hour created in collaboration with TRONIC'S company is ready for small batch production now. The experimental results obtained recently have proved the possibility to reach the level of 0.01 deg/hour. The development of the ASIC, instead of the currently used electronics, and the development of the unpackaged vacuumed silicon sensor are aimed at designing stock-produced MMG with minimum volume and power consumption.

The IANS under design is intended for various applications: land vehicles, small vessels and boats, small airplanes and unmanned airborne vehicles. A prototype of IMU based on the developed MMG as well as an IANS prototype with built-in GPS receiver and a Digital Signal Processor (DSP) have been designed and manufactured. Previously, an experimental IANS on Analog Devices micromechanical inertial sensors was produced. Its software is based on the stationary filters and is similar to the one designed earlier for the loosely-coupled IANS on fiber-optic gyroscopes. The experimental IANS has been tested in a laboratory and on a car. Dynamic test benches were applied for laboratory investigation, and IANS on fiber-optic gyroscopes was taken as a reference at a car test. Furthermore, raw data from micromechanical IMU as well as radial distances, velocities and navigation solutions from GPS receiver obtained at a car test were used for computer simulation of Kalman type algorithms for loosely and tightly coupled integrated systems. As a result the effective modern software applicable for DSP of TMS320F 2812 type and intended for IANS with low performance inertial sensors has been developed.

MMG and MMG-based IANS design as well as the IANS software are considered. The results of the laboratory and automobile tests are presented.

Reliable Vacuum Packaging and Technologies for High Performance Custom-MEMS Gyros

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Abstract

Thanks to silicon-based MEMS technologies, small, lightweight and cost-effective gyros have entered new markets such as automotive and consumer applications and are progressively deployed over a broader range of applications. Even though MEMS-based gyros performances will remain limited compared to Fiber Optic Gyroscopes, their performances, low cost, small size and resistance to shock and vibration will open new guidance and navigation applications. In order to address these market requirements, Tronics Microsystems has been developing new manufacturing technologies, packaging and testing solutions to develop and produce high performance custom products for key partners.

Tronics Microsystems is involved in several custom gyros developments using electrostatic driving actuation of the seismic mass and capacitive read-out of the sensor signal. They are fabricated with DRIE on thick SOI (60µm) substrate with a very high aspect ratio, up to 1:30, and then protected by Wafer Level Packaging. This technology platform, which has been used for producing high performance accelerometers, increases the sensitivity of the moving mass and offers excellent mechanical properties and long-term reliability.

Another feature required by high performance gyros is a controlled vacuum. Indeed, vacuum packaging avoids air particles shocks onto the sensor mass, thereby reducing Brownian noise and thus increasing Q-Factor and sensitivity. In order to obtain vacuum below 1 mTorr, devices are hermetically packaged together with a getter. Once activated the getter progressively absorbs and traps gaseous species thereby maintaining the vacuum level over the long term. This requires an excellent process control since the long-term vacuum may be affected by leakage, materials out gassing or getter saturation. Tronics vacuum packaging technology in LCC housing has been proven stable and reliable below 1mTorr over more than 1000 days of aging studies.

In order to reduce cost and form factor, customers may require realising the vacuum packaging directly at the wafer level. But this new technology leads to internal volume smaller than 1 mm^3 and brings additional challenges which must be overcome. These include wafer bonding hermeticity and wafer level integration of both MEMS structure and getter. Tronics experimental studies have however shown that it is possible to maintain and guarantee a vacuum of a few mTorr over the long term. Comparative assessment of these vacuum packaging techniques, their advantages and drawbacks are presented.

MEMS test is another major cost driver and will continue to represent a significant technological challenge in the commercialization of MEMS. Indeed, controls and tests done by foundries that are limited to typical in-line and on-wafer tests of dies are insufficient. They must be augmented by functional - that is, application-relevant - testing of devices following assembly and packaging in order to reach high overall yields. To address this important issue, we have developed specific dynamic test benches and vacuum packaging ageing procedures.

Tronics Microsystems technologies and latest experimental results will be presented. A special part will deal with the long-term reliability studies based on a resonator test-vehicle and performed both on LCC vacuum packaging and wafer level vacuum packaging.

Compensated Differential CVG

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Abstract

CVG accuracy and cost depend mainly on resonator imperfections after their machining. The basic imperfection parameters are Q-factor mismatch and frequency mismatch. These imperfections can be reduced by additional fine finishing – so called, balancing procedure, but this process has not technological effectiveness and is the major cause of gyro production quantity reduction and cost increasing. Electrical balancing has been developed to increase manufacturability and accuracy especially for CVG MEMS. However, imperfection parameters are changed versus time and temperature that results in CVG accuracy degradation.

Recently, many works have been accomplished on the development of adaptive CVG MEMS control, for example [1] as frequently cited, where control algorithm identifies and compensates for the imperfections in an on-line fashion. Doing that, angle rate measured is estimated by the adaptive observer.

Present work proposes control algorithm to compensate for the imperfections in on-line manner without using observer, but realizing deferential method of angle rate measurement. Differential measurement methods in CVG can be realized by located oscillation wave in the middle between *x* and *y* coordinates, at which electrodes are fixed (for the ring resonator it is under angle 22.5^o to *x* and *y* directions). In this case there are two projection of Coriolis force on *x* and *y* directions with opposite signs, so, angle rate measured can be obtained by half difference of two control signals f_x and f_y sent to *x* and *y* electrodes. It will be shown that under calculation of half difference of the two signals, compensation for the damping cross-coupling terms d_{xy} and d_{yx} occurs. Stiffness cross-coupling terms k_{xy} and k_{yx} compensation are accomplished by sending additional control signals to *x* and *y* electrodes providing phase difference between oscillations along *x* and *y* directions equal to zero. This results in that quadrature signals drive to null for both *x* and *y* oscillations. Oscillation amplitude is keeping constant regardless of present or absent of angle rate, so control signals compensate for additional amplitude caused by angle rate. Zero rate output signal is equal to zero after producing half difference of two control signals f_x and f_y.

The proposed control algorithm performance will be presented in view of test results of the high accuracy metallic cylindrical resonator CVG in wide temperature range and high temperature ramp, when cross-coupling terms change very much. The ability of self-corrected and a large robustness to parameter variations caused by fabrication defects and ambient conditions will be shown by testing the algorithm in the actual CVG.

CVG test results will be compared with FOG test results in the equal environment.

References:

1. S. Park "Adaptive Control Strategies for MEMS Gyroscopes".- Doctorial Dissertation, University of California, Berkeley, 2000.

Quapason: A Low Vibration Sensitivity Vibrating Rate Gyro

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Abstract

The performance of vibrating MEMS gyroscopes are often presented in terms of drift, without indicating what definition of drift is used.

Generally, the given figure corresponds to the lowest point of Allan variance which is the best figure for a given gyroscope. This figure allows comparing different gyros but is not really useful information about the operational performance. In fact, for a lot of applications, the most important figure is the environmentally sensitive drift rate, especially the one depending on applied mechanical vibrations.

This paper analyses the origin of the mechanical vibration sensitive drift rate which is directly related to resonator manufacturing process tolerances. It presents tests results obtained on QuapasonTM, a metallic vibrating gyroscope with a high (resonator volume)/(total volume) ratio.

The 3D design of QuapasonTM ensures relatively good insulation and the resonator is manufactured using cheap and classical machine tools which give relatively accurate precision so that the sensor has very low sensitivity to external mechanical vibrations. The sensitivity of several QuapasonTM with different balancing level will be presented.

Test and Trim Systems of MMG Using Amplitude Modulated Quadrature Torque

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Abstract

Creation of a high accuracy micromechanical gyro (MMG) involves a lot of problems. The most difficult of them are quadrature suppression and trimming of suspension resonance frequencies.

Some quadrature suppression systems for RR-type MMG were presented by the CSRI" Elektropribor" at the Symposium Gyro Technology 2007[1]. In particular, it was shown in case that electrodes are arranged over the rotor combs it is possible to create the torque which is strictly in phase with the rotor oscillation. It is caused by the fact that the MMG rotor functions as a modulator of the electrostatic field force or torque. Unlike the Coriolis forces, the torque created in phase with the rotor oscillation can be named a quadrature torque.

Changing the voltage of the electrodes over the rotor combs results in an amplitude modulation of the quadrature torque. The latter can be used as a test impact on the rotor.

Some test impacts such as amplitude or frequency modulated voltages at electrodes are known to have been used. These signals were built from the signal of the primary oscillation channel. In these cases it was necessary to limit the pass-band of the secondary oscillation channel and use additional filters. The phase lag (an order of 10 °) between the rotor oscillation and the capacitive transducer signal and variation of this lag in the course of operation made formation of an exact quadrature torque impossible.

The quadrature torque as a test impact has the following advantage. It does not render influence on an output signal of a gyroscope as the quadrature is rejected by the synchronous detector of the output channel.

In the paper generation of a quadrature torque is demonstrated by using a few modifications of electrode structures for LL - and RR-type MMG [2]. It is shown how this torque can be used to trim suspension resonance frequencies and the phase of a reference signal of the demodulator in the force balanced MMG and how to continually test serviceability of MMG . Results of the

experimental test of the trimming and testing systems for developed RR-type MMG are presented.

References:

1. T.A. Belyeva et al, "Quadrature Error Reducing Methods in an RR-type Micromechanical Gyroscope" Symposium Gyro Technology 2007, Karlsruhe, Germany,18/19.09,2007, pp.2.1-2.10.

2. Patent RU2320962 G01C 19/56, G01P 9/04 J.A. Nekrasov, ELECTRODE STRUCTURE FOR MICRO-MECHANICAL GYROSCOPE AND MICROMECHANICAL GYROSCOPE ON BASE OF THAT STRUCTURE.

Prototype of a MEMS IMU for AHRS Applications

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Abstract

Northrop Grumman is developing MEMS IMUs for upcoming Attitude and Heading Reference Systems (AHRS) with a target accuracy of 5 °/h for the gyroscopes and 2.5 mg for the accelerometers.

During the technology development phase, prototype single axis gyroscopes have been realized and extensively tested for effects including temperature, acoustic and vibration sensitivities. These devices employ micromachined all-silicon gyroscope sensor chips processed with Deep Reactive Ion Etching. Silicon fusion bonding ensures pressures less than $3 \cdot 10^{-2}$ mbar. Sophisticated analog electronics and digital signal processing condition the capacitive pick-off signals and realize full closed loop operation. With overall bias error <10 °/h (best samples better than 2 °/h), scale factor error <1000 ppm, measurement range >1000 °/s and angular random walk <0.5 °/sqrt(h) the demonstrators belong to the best MEMS gyros produced to date. All current results indicate that stable production of 5 °/h gyroscopes is realistic.

The fabrication technology for capacitive, pendulous accelerometer chips is based on that used for the gyros with only an increase in the enclosed pressure to obtain overcritical damping. Pulse Width Modulation within a digital control loop is used to realize closed loop operation. Accelerometer chips have been tested over temperature with a residual bias error <1 mg and a scale factor error <1000 ppm.

These sensor chips have been integrated into prototype MEMS IMUs whereby the power budget and size of the sensor electronics have been optimized.

In this paper the salient features of the gyro and accelerometer designs will be presented together with an overview of the MEMS IMU system architecture. Measurement results with a focus on environmental characteristics and robustness will be included.

Digital Fiber-Optic Gyros with Piezoelectric Modulator in Close-Loop Feedback

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Abstract

The development and testing results of all-fiber digital fiber-optic gyros (AF DFOG) with piezoelectric modulator are proposed for consideration in this report.

AF DFOG with PEM differs from well-known interferometric FOG with phase modulation of counter waves by electronic system of processing information (SPI). Usually SPI separates harmonics of FOG output sygnal and recovers information about rotation using first harmonic. Another harmonics are using for FOG's units control. The SPI of AF DFOG completely digitally demodulates the output signal of FOG, that allows to determine angular speed of gyro rotation and parameters required for FOG's units control and forms using the PEM control by microprocessor electronic block (MEB), the dynamic close loop circuit.

The results of mathematical modeling of base and «false» interference signals and the algorithms of processing of PINFET information and of forming of close-loop signals are presented in this report. The proposed solutions for creation of allowed to decrease the influence of the «false» interference signals to stability of output characteristics of FOG in 20...30 times.

In real operational conditions of AF DFOG with PEM the changes of operational temperature lead to changes of many gyro's units parameters, that results to decreasing of it's performace stability. The equation of output characteristic of AF DFOG with PEM that takes into account the noise characteristics and the temperature unstability of close loop elements and optical units of fiber ring interferometer (FRI) with PEM was built. Experimental and mathematical researchs, carried out by authors showed, that using the adaptive to enviromental conditions MEB for FRI units control allows greatly to decrease the influence of changing of enviromental conditions to stability of output characteristics of AF DFOG with PEM.

The analysis of features of original MEB and it's algorithtms and software construction in order to provide the SLD working current control and the piezoelectric modulator in close loop circuit control of AF DFOG is given in this report. The one-axis AF DFOG MEB, that uses MPC Cygnal C8051F12 and PLD ALTERA ACEX EP1K100QI208 is placed on single board with dimentions 81.0*81.0*12.0 mm^3.

The analysis of testing results of AF DFOG with PEM, that has fiber-optical coil (FOC) by diameter - 60 mm and length of fiber in FOC by 100 m, PEM oscillation frequency by 70 kHz is given in this report. Is shown that the relative unstability (nonreproductivity, nonlinearity) of pulse value of DFOG with control MEB is 100.0 …200.0 ppm with temperature change from -40°C to + 60°C and with angular rotational speed of platform from ±0.01^0/s to ± 200^0/s. The unstability of zero shift of AF DFOG with PEM in temperature range from -40°C to + 60°C is locate in range from 0.1 to 1.0 angle sec/s when the averaging time of information is 10 s.

Design, and assembly of an Integrated Optic Gyroscopes

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Abstract

The integrated optic gyroscope (IOG) is paid more and more attention for its small size, light weight, potential low cost and convenience of batch manufacture. The integrated optic gyro is acknowledged one of the main trends of optic gyroscope miniaturization. Therefore, the research focuses on the integrated optic gyroscope.

An interferometric integrated optical gyroscope with a sensitive waveguide loop in a silica chip is designed, assembled and characterized. To assemble an IOG, an integrated optic chip must be designed and fabricated firstly. According to the waveguide theories, the silica waveguide dimension and structure parameters are calculated and optimized. The parameters include the width, thickness, index difference, the radius of the curved waveguide and the length of the waveguide loop. To make the waveguide to be a single-mode waveguide at wavelength 1.55μm, the structure of the cross section size of the waveguide is designed to be 6*6μm and the index difference is 0.74%. The radius of the curve waveguide with designed structure should be more than 7mm to assure that the excess loss of the curve waveguide is low enough to be neglected. The optimal loop length is dependent on the loss per unit length, and the higher the loss, the shorter the optimal loop length is. After designing, the chip is fabricated by typical semiconductor process. Except the integrated optic chip, the method to modulate /demodulated the input/output signals of the gyro is another difficult study content, because the loop length of the IOG ranges from 1 percent to 0.1 percent of the loop length of interferometric fiber optic gyro(IFOG), correspondingly, its eigenfrequency is 10^2~10^3 times of the general IFOG. The suitable signal process method is proposed and put in practice. In the signal process solution, the multifunction integrated optic device used in the IFOG is adopted in the IOG system. Finally, an interferometric integrated optic gyroscope is assembled and characterized.

Al Cielo's new FOG based tactical IMU

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Abstract

Over thirty five years have elapsed since the fiber optic gyro (FOG) was proposed by Vali and Shorthill. In these years many different FOGs have been developed and built by many companies in many countries. Thousands of gyros and systems have been used in military and commercial applications. FOGs are competing successfully with existing technologies such as mechanical gyros and RLGs in tactical, navigation and strategic applications underwater, on land, in the air and in space. Not surprisingly technical progress continues to be made with FOGs with the ever present influx of new and improved components form the optical telecommunication and digital electronics field.

Al Cielo is the last company to develop a new FOG and a FOG based IMU and its performance continues to improve on the performance of previous FOG designs. The tactical Al Cielo FOG, and the family of FOGs built on this design, has achieved an unmatched performance to size ratio.

This paper will present preliminary results on the initial production units that were designed for a demanding military application. The day-to-day gyro bias stability and the bias variation over temperature of this tactical IMU is less than 0.5 deg/h. The Angle Random Walk is typically less than 0.02 deg/rt-h and the standard deviation of the Scale Factor repeatability and non-linearity is less than 100 ppm. Details of the design considerations and performance test data are presented.

Recent Investigations on FOG Technology Under Vibration, the Way Forward to Inertial Navigation System

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Abstract

Improving FOG technology behaviour under mechanical environment can be considered as an important technological challenge, as the interferometer is sensitive to very small variations of the overall optical path. To achieve 0.1°/h gyroscopic performances requires solutions to handle as low as 10^-7 relative variation of the optical path.
Nevertheless, this technology has also some intrinsic advantages, such as its capacity to survive to very harsh mechanical shock.

Different possible improvements have been investigated at IXSEA, from the isolation of the optical fiber to external mechanical stress, to the electronic bandwidth and overall FOG loop gain. These efforts have led to interesting results that will be presented : 0.1°/h performances have been demonstrated under harsh mechanical environments (up to 12g rms vibration level) without complex mechanical isolation.

The next steps that will led to the integration of these improvements on IXSEA products will be discussed.

Gyro / Star Tracker Integration for Satellite High-Accuracy Attitude Determination Considering Relative Sensor Kinematics

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Abstract

Overview: This paper deals with satellite attitude determination based on optimal fusion of gyro measurements from an Inertial Measurement Unit (IMU) and star trackers (STR) by stochastic filtering, also known as gyro-stellar estimation. Against commonly made simplifications like rigid spacecraft structures, the paper focuses on attitude accuracy improvement taking relative IMU/STR distortion into account. The results to be presented are part of the current phase-B2 Guidance, Navigation, and Control System development activities for the European Earth observation satellite Sentinel-2.

Motivation: The success of the Sentinel-2 mission strongly depends on the stringent real-time on-board attitude performance of < 10 µrad (2s) per axis, derived from geo-location requirements for images taken by the on-board instrument. Usually, in satellite projects with such high attitude determination accuracy requirements, STRs and IMU are mounted close together to avoid any time-variant relative misalignment. In addition, the satellite structure connecting these sensors is often thermally stabilized in order to reduce misalignment variations to a minimum. But often, like for Sentinel-2, from e.g. the satellite integration and mass distribution point of view, it is preferred to better distribute the sensors within the satellite body. However, these advantages lead to relative STR/IMU kinematics due to thermal variations in orbit. Regarding the high-accuracy attitude determination requirements of < 10 µrad (2s) per axis, the following questions rise:

- What attitude error is induced by unknown time-variant STR/IMU misalignment?
- How can this misalignment be considered in the real-time attitude determination process?
- What is the achievable attitude performance considering time-variant misalignment within the navigation filter?

The content of the paper is focused on answering these questions.

Attitude Estimation Algorithm and Results: The gyro-stellar estimation algorithm is based on an extended error-state Kalman filter fusing sensor data from 4 gyros and 2 star trackers. Time-correlated star tracker measurement noises are considered by an appropriate measurement noise covariance matrix approach.

Monte Carlo simulations have shown that considering 100 µrad time-variant misalignment amplitude per axis by filter tuning increases the attitude error by 82% per axis. Considering time-variant misalignment by an appropriate dynamical model within the filter increases the attitude error by only 6% per axis despite limited observability of the filter state. This result clearly reflects the capability of this approach. A detailed presentation and discussion of the proposed approach will be given in the paper.

Comparison of Different SAR/INS Integration Techniques

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Abstract

Integrated navigations systems are widely used in aircraft or missile systems to provide accurate navigation information containing position, velocity and attitude. These navigation systems rely on two or more sensors, which are combined in the navigation filter. An inertial navigation system provides accurate relative position updates along short periods of time. To ensure long term accurate and autonomous navigation information a radar altimeter or synthetic aperture radar (SAR) is used.

In this paper a SAR/INS navigation system is introduced. A synthetic aperture sensor captures the earth surface in range and cross range coordinates. The captured image is then transformed into earth coordinates and matched to a map which contains specific well visible and unambiguous features like crossroads or courses of rivers. The position shift between the captured SAR image and the reference feature is used to aid the navigation information. Many matching techniques are described in literature. Thus, it is assumed that matching algorithms exist and that a match between the SAR image and the reference feature containing feature position as well as feature position accuracy can be achieved.

This paper concentrates on the processing of the detected position shift between the SAR image and the reference feature. It is shown, that it is possible to provide three-dimensional update information from SAR measurements. In a first step a standard extended Kalman filter (EKF) has been implemented. The nonlinearity of the SAR imaging geometry and the measurement equations are examined in a second step. An error in height estimation leads to an error in the estimated feature position in a nonlinear way. Higher order terms in the measurement equation may become significant in the presence of larger height errors. Due to this fact a sigma point Kalman filter (SPKF) was implemented and compared to the extended Kalman filter.

Since feature matching may not be successful in the absence of manmade features e.g. in hilly regions a combination of SAR/INS and radar altimeter is recommended. Radar altimeter measurements ensure accurate height information and are able to autonomously aid the

navigation solution in regions of rough terrain by comparing terrain height measurements to a reference height map whereas SAR prevents increasing navigation errors over smooth terrain, where manmade features like crossroads commonly occur more often.

The performances of EKF-based and SPKF-based SAR/INS navigation systems will be compared in numerical simulations. Additionally simulation results of a combination of SAR/INS and standard terrain referenced navigation will be presented.

Integrated INS/GPS/Optical Camera for UAV Control

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Abstract

Miniature Strapdown Inertial Navigation System (miniINS) with inertial microelectromechanical systems (MEMS) is widely used in autopilot design for control of different unmanned aerial vehicles (UAV). This system is characterized by low cost, small overall dimensions and low power consumption. However, the use of this system in an autonomous mode is hampered since instability of MEMS sensor characteristics causes fast accumulation of errors in determination of navigation data. The effective approach to solve this problem is integration of miniINS with different external measuring devices like GPS navigation, magnetic compass, airdata sensor.

The most typical correction method of low cost inertial systems presumes the use of a correction algorithm, that exploits feedback on full vector of error estimates, formed by the state observer like Kalman filter (KF). The results of experimental investigation of accuracy of integrated miniINS, which is the main component of the autopilot are presented in the paper. The autopilot is developed in National Aerospace University "KhAI».

The developed autopilot provides measurement of kinematic and dynamic parameters and control of the UAV. The autopilot includes the inertial system, magnetic compass, GPS-receiver, airspeed sensor and barometric altitude sensor. The use of the inertial system as the main component of the autopilot provides:

the required flying accuracy with capability of UAV destination to the desired waypoint at a given time;

tracking the predefined path.

These flight tasks cannot be solved by the use of the GPS-receiver coupled with yaw gyro.

According to the results of the experimental accuracy investigation of miniINS, using correction algorithm with the feedback on full vector of error estimation of the system, it can be concluded that this system has required stability margin in dynamics of error estimation and robust properties to "poor" measurements.

Thus, the use of integrated miniINS with MEMS-sensors as the main component of the autopilot allows providing the required accuracy of determination of the UAV attitude, position and velocity.

The INS/GPS integration with video camera allows to improve INS error correction. In this case the additional measurements of UAV motion with respect to the ground surface and angular

orientation of velocity vector in camera plane can be obtained. Thus, the problem of heading channel can be solved by determination of UAV sideslip angle using the displacement of camera line of sight on the ground surface. This displacement can be determined by using video images of frame flow from the camera. UAV motion with respect to the ground surface is derived by using cross-correlation function of two sequential frames of the video flow. The displacement is determined for two coordinates of camera plane that allows to calculate a UAV sideslip angle. Correction of the heading channel is carried out using the GPS track angle and calculated sideslip angle. The second problem which can not be solved by using standard correction tools with baro altimeter and GPS is determination of UAV true altitude over the ground surface. The camera perspective, scaling objects depending on their distance or altitude contains the information about UAV altitude. The optical channel allows to estimate the UAV true altitude over the ground surface by using the ratio between GPS velocity and velocity received from the optical channel.

Navigation System of a UGV Based on Inertial Sensors and Image Data of a VTOL-UAV

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Abstract

Over the last years, the interest in small unmanned vehicles has increased constantly. The possible application areas of UGV's (unmanned ground vehicle) as well as UAV's (unmanned aerial vehicle) are widespread. They are especially useful for security and rescue operations for example in cases of industrial or natural disasters like earthquakes or fires and can significantly reduce the risk for the human rescue teams.

This paper describes the determination of a robust navigational solution of a small UGV in an urban environment. By teaming with a UAV, this is even possible in the cases of no GPS coverage or bad signal quality as it happens especially in urban canyons.

The team consists of a small, wheeled UGV and a small four rotor VTOL-UAV with a takeoff weight below 1 kg. The UAV is equipped with an onboard navigation system that integrates a 3 axis MEMS-IMU with a GPS receiver as well as a barometric altimeter and a magnetometer. The two vehicles communicate via a digital data link. A digital camera is mounted on the chassis of the UAV and is pointing towards the ground. The UAV is completely self-stabilized and is additionally capable to follow autonomously a pre-defined trajectory.

The UAV accompanies the UGV in sufficient height to ensure good GPS signal availability. In the first step, the acquired image data stream is processed in order to detect and track the UGV over time. Furthermore, a geo-location algorithm is implemented that enables the ongoing determination of the UGV's position with respect to a geo-referenced coordinate system. This information is transferred via the digital data link to the UGV where it allows the determination of reliable position information even if no GPS data is available in the ground vehicle.

This paper investigates the setup of the UAV/UGV-team as well as the image processing and geo-location algorithms. Additionally the aiding of the UGV navigational system is covered. After a detailed description of the used algorithms the performances of the particular parts of the setup and also of the whole system are illustrated with experimental data.

SINS with Rotating Fiber Optic Gyro

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Abstract

In order to satisfy high precision position of Strapdown Inertial Navigation System (SINS), it is developed for the SINS with rotating fiber optic gyro. The system is composed of inertial sensors, high speed navigation computer, input and output ports and so on. The inertial sensors are fiber optic gyros and quartz accelerometers made from Sichuan Institute of Piezoelectric and Acousto-optic Technology. Navigation computer is made of high-speed floating point Digital Signal Processor (DSP), Field Programmable Gate Array (FPGA), and Microchip Control Unit (MCU). FPGA is used to acquire signals from inertial sensor, dual port RAM and logical circuit of DSP. The function of DSP receives data of inertial sensor from FPGA, process digital signal, corrects the errors of gyros and accelerometers, calculates the SINS equations and twenty-fourth order Kalman Filter, and finally writes the results of navigation parameters to FPGA. Communicating between dual port RAM and DSP, MCU is responsible of data receiving and input and output. The inertial sensor is located in a rotation configuration. Through rotating inertial sensors and acquiring multi-location information, orientation can be determined rapidly. By rotating inertial sensors continuously, gyro drift coefficients, scale factor errors and accelerometer biases can be estimated, they are used to correct the errors of inertial sensors, and improving the performances of SINS. Accuracy of rotating fiber optic gyro SINS in laboratory is head error 0.2°, attitude error 0.05°, placement error 2nm/8hr. The system can be applied to various navigation of vehicles and ships.

GPS-Denied Navigation Error Budget Factors

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Abstract

Land-based positioning systems sometimes have to operate in environments without reliable GPS signals. The Applanix Land Survey position and orientation system (POS LS) is capable of delivering high-performance navigation information even when GPS data are not available for extended periods of time, such as in jungle and heavily forested areas. POS LS includes a navigation-grade IMU mounted into a backpack suitable for one-person operations. POS LS uses zero velocity updates (ZUPT) as the prime aiding source when stationary.

POS LS is being upgraded to operate entirely within GPS-denied environments (buildings, ships, etc) for search and rescue operations by emergency responders and war fighters. The following factors are identified as important contributors to the navigation error budget:

- IMU performance
- ZUPT operations
- Position fix operations
- IMU alignment operations
- IMU error modeling
- IMU orientation with respect to local geographic frame
- Gravity model errors
- Clock errors
- Environment

The study, that includes test results for the Honeywell CIMU and HG9900 – based POS, evaluates the contribution of each factor and combination of factors to the system error budget. In particular, it is shown that

- ZUPT variable setting (parameters of ON/OFF and measurement update algorithms) leads to satisfactory performance not only during land operations, but also when working on docked ship.
- Proper Kalman filter error model selection substantially decreases negative effect of gravity model errors.
- Gravity model effect during one-person operations is practically eliminated when dramatic changes in IMU orientation (such as switch from walking to crawling) are immediately followed by a ZUPT.

An Extended Kalman Filter for Improving Angular Motion Knowledge in a Multiple Distributed IMU Set

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Abstract

The quality of angular motion knowledge is an essential part to achieve an accurate position and attitude solution. Unfortunately, high quality gyroscopes have high cost, high power consumption, large weight and large volume. Using accelerometers to infer angular rate is a possible solution but it has some difficulties. Difficulties include increased computational load, increased size of inertial sensors. Moreover, most of the current approaches consider computing angular velocities by integrating angular accelerations only, while ignoring direct quadratic measurements of angular velocities. Quadratic angular velocity terms do not have accumulative error as in case of integrating angular acceleration. The advances in both processing technology and MEMS inertial sensors reduced the complexity of implementing a multiple inertial measurement unit IMU system. It is time now to apply these advances to achieve high navigation performance and at the same time get costs greatly reduced.

In this paper we give a solution for benefiting from angular information vector resulting from the multiple distributed IMU set (MDIMUS) described in our paper (Gyro Symposium 2007). This configuration consists of three non-planar distributed IMUs and one concentric IMU. We have shown that concentric and distributed IMU sets have comparable performance in case of not benefiting from the angular velocity information vector resulting from distributed accelerometers computed based on lever arm effect. This special MDIMUS configuration has interesting features that makes us consider it as principal configuration. Using such a configuration produces an angular information vector that consists of three angular accelerations and six quadratic terms of angular velocities. In the deterministic case, we can extract the angular velocity accurately and easily, but in case of stochastic measurements of accelerometers as it is in reality, we need to apply estimation techniques to solve for angular velocity.

The novelty of this research is combining both of computed angular velocity vector and directly measured angular velocity vector through a filter scheme which efficiently fuse all the available redundant angular data. The main goal is to improve the angular velocity knowledge and hence improve the over-all navigation performance. The combination is necessary because the extracted angular velocities from distributed accelerometers has undetermined sign solutions and the aid of gyros can force the convergence to the right sign of solution. The aid can be provided by low cost gyros as we seek the correct sign convergence from gyros. We propose an extended Kalman filter (EKF) for the fusion. The EXF setup has a prediction based on angular accelerations as input and a measurement update based on an augmented measurement vector which consists of 6 quadratic terms of angular velocity and direct gyro outputs. A simple but adequate IMU model that describes IMUs errors has been implemented in our simulation covering the different categories of IMUs available in the market. Appropriate estimation results will be presented to validate the functionality of the design.

Ship Hull Deformation Gage Based on Gyro Technologies

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Abstract

The efficiency of applying a number of technical aids onboard marine vehicles (ships, vessels, etc.) substantially depends on proper account of navigational and dynamical parameters of these aids motion. In order to suppress roll and pitch influence on the accuracy of technical aids, gyro stabilization systems (GSS) are generally used. Traditionally these systems solve the following parameters generation problems:

- roll, pitch and yaw angles and angular rates,
- speeds and displacements caused by the roll, pitch and orbital motion influence on the ship.

However, GSS generate these parameters for the mounting locations of GSS gyro devices. Moving away from the posts result in hull deformations which lead to additional errors in determination of attitude parameters (roll and pitch angles, heading, relative bearing). At present recording of deformations is provided by several GSS mounted onboard the ship and arranged at the areas, where the most error sensitive GSS data users are installed. Nonoptimality of such problem solution is evident as regards the cost and reliability criteria. That was the reason to develop a hull deformation gage (HDG) – a small-sized and low-cost gyro device, which is capable to generate the required parameters at the users location.

The following methods of deformation measurement are known:

- use of two devices based on three-dimensional meters of angular rate vector,
- use of group gyro stabilization system comprising two or more gyro devices,
- measurement on the basis of data from GNSS receivers with spaced antennas.

Limitations of these methods are considered. A hull deformation gage modification is proposed. It is based on an inertial gyro vertical constructed on the strapdown principle and integrated with the central GSS by speed, angular and position measurements. Fiber-optic gyros and accelerometers of middle accuracy class are used as HDG sensitive elements (SE). The block diagram of HDG is presented, the inertial loop of which is tuned to Schuler frequency and has substantial distinctions from the standard modification of a strapdown INS, including those aimed at determination of static and dynamic deformation components.

As a result, correcting signals and additional elements are introduced into the inertial loop:

- speed from GSS with the aim to generate angles of static deformation, decrease the vertical errors caused by scale factor errors and accelerometer offset,
- attitude parameters from GSS (roll, pitch and heading) for generation of dynamic deformation component and substantial decrease of the gyro drifts influence on the vertical error,
- integrating filter with the aim to extract dynamic deformation component, generate attitude complete angle at the user's location and compensate the gyro drift.

The simulation made it possible to determine the SE characteristics required and accuracy levels expected of the output parameters under various service conditions and accuracy characteristics of central GSS. Comparison characteristics of GSS and HDG and their SE are cited.

HDG computing aids are constructed with the use of signal processor for solving "quick" kinematic equations integration problems.

Peculiarities of bench tests with imitation of static and dynamic deformations are stated as well as results of HDG accuracy tests. Sea trials materials are presented, in this case new information on the ship hull deformations under wind forces, ship maneuvering and shock disturbances has been obtained. Some sources of static and dynamic deformations are specified.

The results obtained have confirmed the consistency of the HDG scientific and technical implementations proposed with provision of deformations measurement accuracies required at the level of units of angular minutes in real sea conditions. In conclusion the intended application areas of the new article based on gyro technologies have been given.

Extended Bearing-Only Algorithm for Target Motion Analysis

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Abstract

The problem of determining the position and velocity of a given object (frequently called target), in order to keep track of it, and predict its future position, is as old as the man history. Such problem is known as Target Motion Analysis (TMA), and it is totally dependent on the quality of the sensors involved in the object detection, the algorithm used to handle the data acquired and the quality of data (attitude, position and speed) related to the own observer.

The TMA problem ranges from very atavistic human activities to very evolved attitudes. Primitive man uses their eyes and ears to detect, and brain to calculate future position. It was livelihood. Prediction of the position of animals to hunt them was capital to survive. Concerning defense subjects, targeting naval vessels and aircraft are paramount factor for tracking, ballistic or tense shooting, and even for homing missiles and torpedoes. Just considering material aspects, the values involved have magnitude of hundreds of million dollars. At the very end, regarding the future of the humanity, astronautics and deep water explorations are the legitimate and authentic users of TMA. Determining the position of celestial matter, attitude of deep submerged vehicles, spacecraft's structures and docking stations and so forth are hot topics.

This paper introduces a new method to perform target motion analysis, based on an Extended Bearing-Only Algorithm (E-BOA). The method is based only on the use of the target's bearing and current position of the observer. The use of just bearing grants to the method, passive detection, which is fundamental in many aspects.

The method uses a modified pseudo-linear estimator to optimize the best solution search. The estimator was built using evolutionary techniques and genetics algorithms (GA), which consider the families of estimated positions as "generations" that shall "evolves" according to certain patterns.

Another feature of the method is the use of the wavelet concept as denoising strategy to overcome lack of precision of the inertial navigation system (INS) used to determine the position of the own observer. The wavelets were used also as filters to reduce noise, and avoid lack of precision and the common variance of the sensor used to detect the target.

The method was implemented as a fast high-level Windows™ application, which collects data from the sensors and the INS via Universal Serial Bus (USB) interface. The interaction with the operator is granted by the Windows platform.

Simulated and real data were submitted to the method and the results obtained are more accurate, precise and robust than those recently published by different authors.

A Nongyroscopic North Finding System

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Abstract

The determination of the azimuth of a vehicle, as an essential element of navigation for example, is usually accomplished by gyroscopes. The attainable accuracy of the north finding process is limited by the constant drift of the gyros. Other azimuth determination techniques which are fast and accurate enough as well as cost-effective are therefore a topic in current research.

This paper describes a north finding system utilizing accelerometers instead of gyroscopes. The sensors are orthogonally mounted on a rate table, which rotates at a constant speed. The principle of operation of the measurement unit is based on the Coriolis acceleration, which is induced since the sensors move in the rotating reference system of the Earth. The variation of the measured Coriolis acceleration in time yields the required azimuth information. In contrast to gyroscopic north finders the attainable accuracy is insensitive to sensor bias errors, thus allowing the application of low-cost MEMS sensors.

However, other error sources could reduce the accuracy of the north finder substantially. The gravity vector is partially coupled into the sensor signal due to possible sensor misalignment. As this disturbance shows the same frequency as the Coriolis signal, common filter techniques cannot be utilized for rejection. The rolling bearings of the rate table represent a further error source. Because of their geometrical imperfections, they generate periodical vibrations which interfere with the Coriolis signal as well.

By means of a mathematical model, which characterizes the influence of the aforementioned disturbances, it is shown that by simultaneous measurements with several accelerometers the Coriolis signal could nevertheless be obtained with high accuracy. The individual signals are processed in such a way that the disturbances compensate each other. The experimental setup not only allows the finding of the azimuth but also the determination of the vehicle's attitude. Unknown parameters, like sensor misalignments, scale factors and the positioning of the sensors on the rate table are determined by a calibration process of the system.

Finally the experimental setup is described and measurements are presented. The results validate the derived model and show that the Coriolis signal, and hence the azimuth, could be accurately determined for different attitudes of the measurement unit.