LOW COST INERTIAL REFERENCE SYSTEM BASED ON FIBER GYROS WITH GPS-AIDING

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ABSTRACT

Inertial reference systems play an important role within modern flight control and navigation systems. This is especially true for strapdown system mechanizations, which deliver complete multilevel informations - acceleration, rate, velocity, position and attitude - for any needed coordinate system.

Due to latest progresses in the field of development of fiber optic gyros and low cost satellite navigation (GPS) receivers it is now possible to design an all solid-state low cost solution for a flight control and navigation reference system.

The presented system consists of an 'integrated fiber optic gyro strapdown/ magnetic sensor/ GPS system'. A functional description and the system mechanization are presented together with first results from system simulations. The ground and inflight alignment methods are discussed.

I. INTRODUCTION

Within the past years two very important developments in the field of flight guidance influenced avionics achitecture. The inertial strapdown technology allowed in principle the integration of the navigation and the flight control sensor task. On the other hand the development of satellite navigation allows for the future the solution of the navigation accuracy/cost problem. Needed high navigation performance will not be bounded to the costly laser gyro strapdown solution. The parallel GPS- and fiber optic gyro programs at SEL are destinated for a lowcost/high accuracy solution for the navigation and flight control problem.

This paper will present the status and the preliminary design of an integrated GPS-/magnetic sensor-/fiber optic gyro (FOG) system approach. This all solid state navigation system is built around a FOG-strapdown inertial unit. For a detailed description of the GPS-receiver development see /1/.

The program time schedule will be end of 1987 for hardware realization and first laboratory tests and approximately end of 1989 for completing field tests.

II. FIBER OPTIC GYRO DEVELOPMENT

In 1980 SEL started the development of fiber optic gyros, see /2/. Two different types of gyros mainly differing in their readout method - the phase modulated and the frequency modulated one - were investigated. The second type demonstrated a high scalefactor stability (see /3/) combined with an improved drift rate of about 1 deg/h. No manouver dependent drift rates - as for instance acceleration proportional drift - were observed. The measuring noise is represented by a pure normally distributed signal. Up to now the gyro performance is limited by temperature dependent bias variations. For this reason the sensor temperature has to be measured for drift compensation by use of an adequate thermal model.

Figure 1 shows the configuration of the SEL-frequency modulated FOG. It is a Sagnac type interferometer in its reciprocal configuration with two Bragg-cells, a single mode polarization-preserving fiber, a laserdiode and a low noise photodetector. Fiber length is 960 m. The coil diameter is 84 mm corresponding to an angular increment of about 3 arcsec/pulse.

The two main FOG verification problems
- a stable 90 degree phase bias for a high sensitivity and
- a linear phase compensation loop corresponding to a mechanical gyros rebalance loop for high scalefactor linearity and stability

are solved using two Bragg modulators, one of them with frequency switching. The basic idea is that different steering frequencies result in a nonreciprocal phase which is proportional to the frequency difference of the counterpropagating waves in the optical loop. The frequencies are periodically switched. The frequency difference is chosen to produce a nonreciprocal phase shift of +/-90 degrees changing the cosine intensity characteristic at the photodetector element to a sine characteristic. The readout signal is obtained within a control loop consisting of a detector signal amplifier, a bandfilter and an integrator which shifts the VCO-output frequency to null the rotation induced Sagnac phase. The digital output signal is calculated from the applied modulation frequencies.

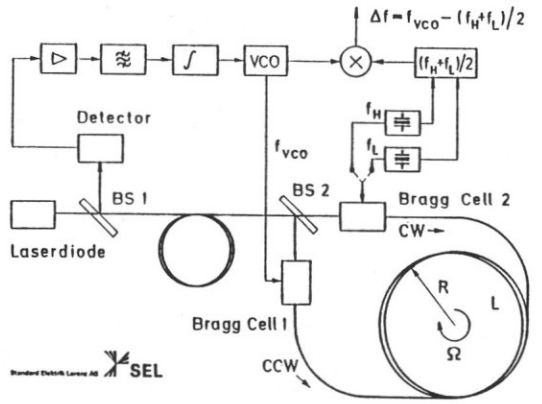

Figure 1: Principle of operation of the SEL frequency modulated fiber optic gyro

Figure 2 shows the assembled FOG-sensor. For operation two electronic boards have to be added.

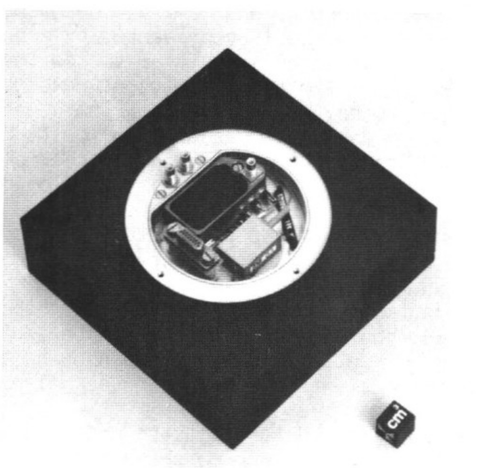

Figure 2: SEL frequency modulated fiber optic gyro

III. GPS-RECEIVER DEVELOPMENT

After verification of a classical analog GPS-receiver in 1984 the development of a new receiver concept which has the impact of reduced costs and improved reliability was started at SEL. By digitizing the frontend output signal directly a maximum of functions can be performed by programmable digital circuitries. This concept was validated by means of experimental and theoretical investigations. Using general terminology the receiver is characterized as a four channel, fast scan multiplex receiver. It measures the pseudoranges and decodes the data of four satellites in order to determine the position and secondly the velocity and the exact time.

Figure 3 shows a block diagram of the new concept. The RF-unit converts the input signal of 1.5 GHz to an IF of 10 kHz. The IF-bandwidth is about 1MHz. The digitizing (1 bit quantization) is performed directly at the IF-output and the following function realized by an exclusive OR is the multiplication of the received signal with the internally generated C/A code. All GPS-codes are derived from one ROM. All other main functions like

- carrier acquisition and tracking
- code aquisition and tracking
- data demodulation

are carried out by the miroprocessor. The digital Costas' loop and the digital tau-dither-loop are performed by software.

One hardware channel is operating in the fast scan mode with a dwell time of 1 ms per satellite. Four programmed Costas' loops and four tracking loops remain locked to the four selected satellites (four pseudo channels).

As the loops are realized in software it is easy to implement variable loop bandwidths. This feature is exploited to optimize the receiver performance during acquisition and tracking phase. Narrowing the loop bandwidth during tracking for example reduces the pseudorange error due to noise. A steered wider bandwidth allows quick pull-in during acquisition.

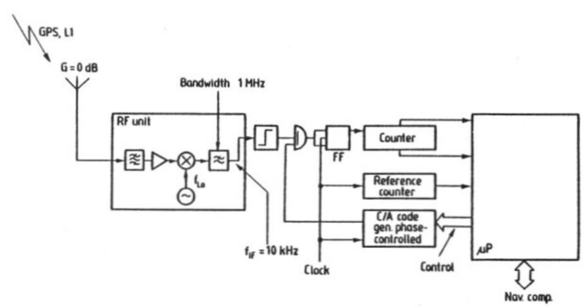

Figure 3: Functional diagram of the low-cost GPS-receiver

Four outputsignals are gained from a Kalman-filter using the measured values of individual satellite pseudoranges. Using a model with appropriate state representation of the vehicle dynamics, this filtering process allows reasonable reduction of disturbances on the navigational informations.

IV. EXPERIMENTAL INTEGRATED FOG-INS/MAGNETIC SENSOR/GPS-SYSTEM

The functional blockdiagram in Figure 4 shows the experimental setup. INS and GPS-subsystems are functionally integrated. Airdata are primarily used - as in all GPS- or INS- systems - to stabilize the systems altitude channel and secondly to allow drift angle computation for the ARINC 429 output. A control unit is used for switching the different operational modes. During the experimental phase a ARINC 429 simulator is used as external online readout and command unit. It allows display and registration of all internal data which are of interest.

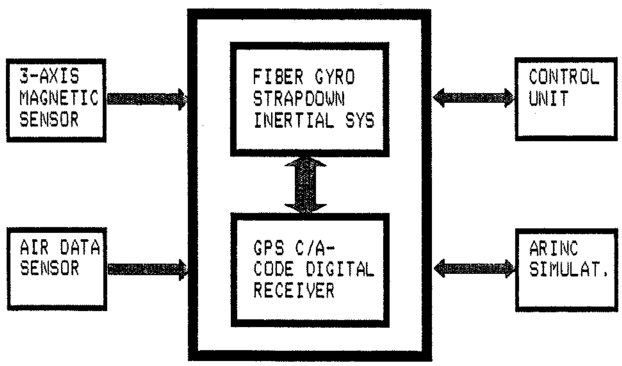

Figure 4: Experimental FOG-strapdown/ magnetic sensor/GPS - system

STRAPDOWN SOFTWARE OPTIMIZATION

The work on strapdown system evaluation for the FOG-application started in 1985. During the first phase the well known strapdown algorithms (see /4/) were optimized for FOG-application. A special software tool was developed to investigate the navigational software and to allow direct transfer of evaluated software modules to the INTEL 8086 target processor with mathematic coprocessor 8087.

The blockdiagram in Figure 5 shows the structure of the so called Navigation Software Development System. The very complex input data are handled by a special input processor which allows easy modification of single coefficients out of the total set and inputdata-file control and documentation. Different types of carrier movements including sinusoidal movements can be carried out. A geometrical displacement of the sensing unit with respect to the center of movement of the carrier causing additional acceleration signals is also modelled within the flight path generator which delivers all reference data together with the needed correct sensor signals, as for instance the rate values for the gyros and the acceleration values for the accelerometers. These signals are falsified by the sensor error generator which delivers its signal to the real time navigation software which has to be optimized with respect to

- algorithm (numerical approx.)
- programloop timings (sampling)
- quantization (sensor digitizing)
- roundoff (word length)

Navigation signal errors are analyzed by the signal processing software which uses standardized file inputs/outputs for multiloop signal analysis.

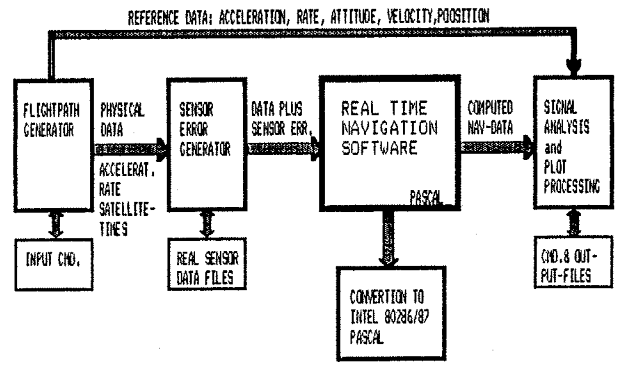

Figure 5: Navigation-software development system

As an example see Figure 6. It shows the angle error as function of time for a third order quaternion verification of the strapdown attitude computation including earth rate compensation (sensor errors not included) after optimization of roundoff errors. Inputs are 0.01 degree/s rates about all three axes. Computation rate is 50 c/s.

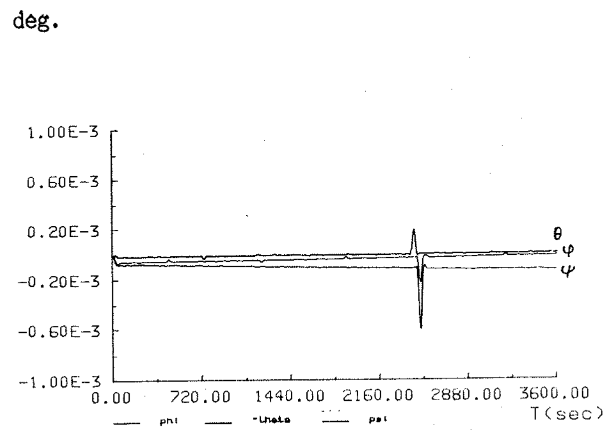

Figure 6: Attitude angle errors due to strapdown software over one hour (.01 deg/s input for all axes)

FUNCTIONAL DESIGN

The integration of all internal functions of the inertial system can be studied from Figure 7. The error compensation model is updated during the alignment phase within a calibration sub mode. As indicated a temperature modelling is needed for the FOG-sensors. All sensor error calculations are carried out at 100 c/s. The corrected signals are used within the 50 c/s strapdown attitude and velocity calculations (third order quaternion algorithm). The combination of three axis magnetic sensor data, airdata-altidude data and GPS data is performed within the integrated navigation calculation software job. This contains the optimal filtering process with a high-order-Kalman-filter which is currently under test. The ARINC 429 output data calculation is performed at a lower rate of 25 c/s.

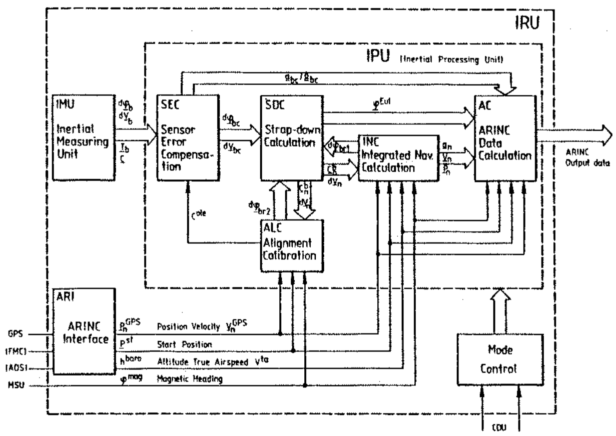

Figure 7: Functional diagram of the experimental system

ELECTRONICS SETUP

The INS-electronics design can be seen from Figure 8. Two processors - both equipped with floating point coprocessors - are coupled via a dual port memory sharing the jobs of interfacing, strapdown computation in CPU-1 and Kalman filter-data integration in CPU-2 .

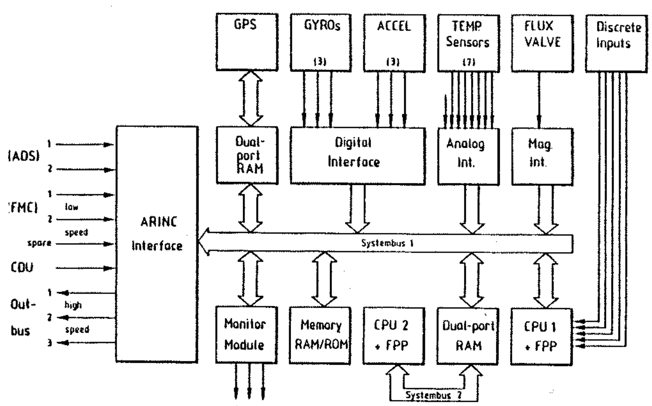

Figure 8: Principal arrangement of the experimental system electronics

V. PRELIMINARY SYSTEM ANALYSIS

On the first view the system suffers from the limited north alignment accuracy due to the 1.0 degree/hour gyro drift which corresponds to an error angle of about 5.7 degrees. On the other hand a 1.0 degree/hour gyro may be sufficient for the filtering and extrapolation of GPS data. The idea is now to limit the start off azimuth error angle by an additional three axis magnetic field sensor to a value of about .2 to .25 degree. This value is only true for three axis error modelling and optimal filter implementation which allows estimation and compensation of hard and soft magnetic field disturbances. By storing estimated magnetic sensor error coefficents in a nonvolatide memory the start on values of azimuth misalignment should be in the order of about 0.5 degree and should settle to the projected value of about 0.2 degree within 10 minutes of flight with GPS-receiver operation. The simplified strapdown alignment error model in Figure 9 confirms that the accuracy mainly depends on the east gyro drift rate.

Because of the small accelerometer bias values of about 0.0001 g they don't contribute to the error budget. The driftrates of the east and the north gyro are damped within the horizontal loops with a magnification K which depends on the actual Kalman filter estimation. The azimuth angle error is bounded as discussed before by the magnetic sensor.

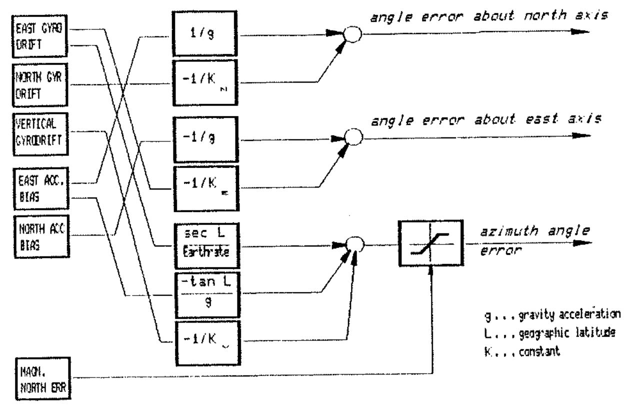

Figure 9: Simplified strapdown system alignment error model

The expected azimuth angle error over time is shown in Figure 10. Going through a leveling and a magnetic sensor azimuth transfer to the strapdown system after system switch on the gyro drift will be estimated before automatic switching into the navigation mode. During the navigation mode a inflight alignment will bring down the alignment errors to smaller values depending on flight path changes. During a time period with no GPS operation the error will increase but be limited by the magnetic field sensor data. The time constant of this increase has to be determined during the planned flight tests.

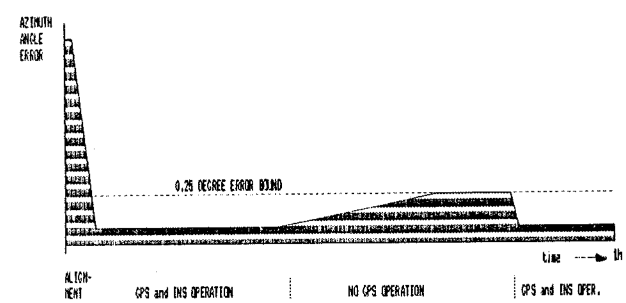

Figure 10: Azimuth angle performance (from simulations)

The simplified error model for inflight alignment in Figure 11 demonstrates that the mixing of GPS- and INS- data has to be carried out on the velocity level. Both velocity vectors are combined in principal by cross product multiplication (vertical velocity loop damping by barometric altitude not shown). The two dimensional velocity error angle (the third angle: rotation of the vector cannot be detected) can be used after transformation to bodyfixed (sensor-) coordinates for the generation of rate signals which may be added to the measured gyro signals for correcting the strapdown-transformation matrix. The needed third correcting angle signal will be generated by use of the magnetic sensor data. This system design avoids the problems which are associated with the limited and manouver dependent state observation which is given for a system without the additional magnetic field sensor.

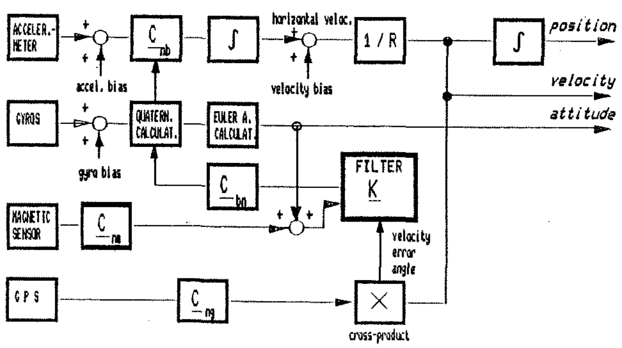

Figure 11: Simplified inflight alignment error model

The forecast for the navigational accuracy in terms of position is given with Figure 12. Allowing the Kalman-filter to estimate all modelled system errors during a first flight phase an INS extrapolation accuracy corresponding to a time period of about 25 minutes for a 2 nm error-limit and no GPS-receiver operation is expected. This is regarded to be sufficient for operation.

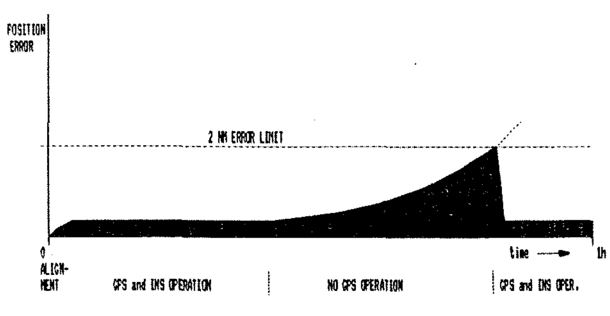

Figure 12: Position error performance (from simulations)

VI. FUTURE SYSTEM DESIGN

In order to aim a low cost integrated navigation system with a similar low weight, volume and power consumption an early hardware redesign was started. Figure 13 shows the projected setup which is integrated within only one ARINC-600 box (experimental system : two boxes). This will be achieved using todays packaging and solid state technology.

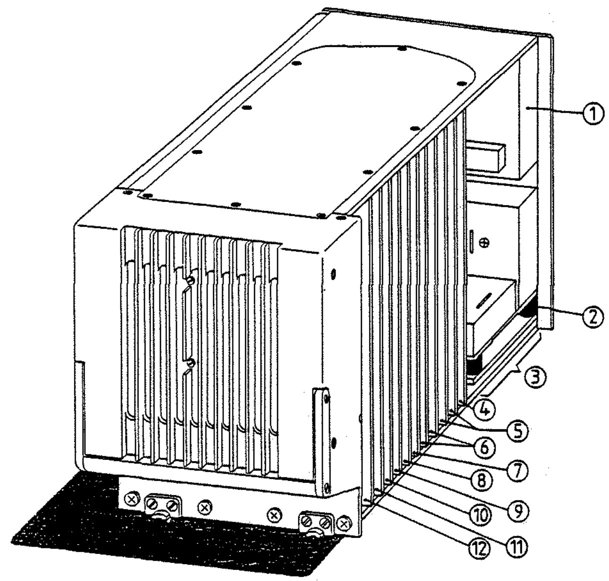

Figure 13: Planned integrated FOG-INS-/ GPS-/ magnetic sensor- navigation system set up
(1) connector unit
(2) shock mounted IMU-fixture
(3) FOG-gyro and accelerometer measuring unit
(4) accelerometer rebalance loops and digital readout electronics
(5) FOG digital electronics
(6) FOG RF-electronics
(7) INS-strapdown-processor
(8) dual port memory
(9) GPS-processor
(10) interface/ bus-controller
(11) GPS-digital signal processing
(12) GPS RF-section

VI. CONCLUSION

The combination of a fiber optic gyro strapdown system with a digital GPS-receiver and a magnetic sensor allows a low cost solution for a high accuracy all solid state navigation system with extremely good maintainability figures. The inertial system extrapolation facility will guarantee continous operation even in the case of disturbed GPS-receiver operation. The startoff azimuth angle accuracy is limited due to the use of 1.0 degree/hour drift gyros. The use of a magnetic sensor will limit this error to a minor value and supports the inflight alignment procedure. The complete system will be designed to fit into one ARINC-600 box.

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