Tuning of MEMS Gyroscope using Evolutionary Algorithm and "switched drive-angle" method.

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Abstract— [12] We propose a tuning method for Micro-Electro-Mechanical Systems (MEMS) gyroscopes based on evolutionary computation that has the capacity to efficiently increase the sensitivity of MEMS gyroscopes through tuning and, furthermore, to find the optimally tuned configuration for this state of increased sensitivity. We present the results of an experiment to determine the speed and efficiency of an evolutionary algorithm applied to electrostatic tuning of MEMS micro gyros. The MEMS gyro used in this experiment is a pyrex post resonator gyro (PRG) in a closed-loop control system. A measure of the quality of tuning is given by the difference in resonant frequencies, or frequency split, for the two orthogonal rocking axes. The current implementation of the closed-loop platform is able to measure and attain a relative stability in the sub-millihertz range, leading to a reduction of the frequency split to less than 100 mHz.

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1. INTRODUCTION

Future NASA missions would benefit tremendously from an inexpensive, navigation grade, miniaturized inertial measurement unit (IMU), which surpasses the current state-of-the art in performance, compactness (both size and mass) and power efficiency. Towards this end, under current development at JPL's MEMS Technology Group are several different designs for environment tolerant [10], high performance, low mass and volume, low power MEMS gyroscopes. The accuracy with which the rate of rotation of micro-gyros can be determined depends crucially on the properties of the resonant structure. It is both difficult and expensive to attempt to achieve these desired characteristics in the fabrication process, especially in the case of small MEMS structures, and thus one has limited overall sensor performance due to un-avoidable fabrication inaccuracies.

The accuracy with which a given vibratory gyroscope can determine the true inertial rate is crucially dependent on the properties of the two degree-of-freedom resonator. The problem with tracking orientation using only gyros is drift such as gyro bias which creates a steadily growing angular error, gyro white noise and gyro bias instability [13]. Today's commercial grade gyros (devices used in automobiles, camcorders) can only be used for a minute before the drift becomes distracting and the user needs to reset the orientation tracker. Tactical-grade gyros used in short-range missile guidance are good enough for head-tracking for more than 20 minutes. Navigation-grade gyros are required for space applications. Unfortunately, the price, weight and power ratio between navigation, tactical and commercial-grade gyros follows the performance ratio. MEMS gyroscopes will be gradually closing in on the performance using techniques presented in the paper.

One way to reduce the rate drift is to increase the sensitivity or scale factor relating volts out to radians per second of inertial input [9]. The scale factor is maximized when the resonant frequencies of the two modes of freedom of the MEMS gyroscope are identical. Symmetry of construction is necessary to attain this degeneracy. However, despite a symmetric design, perfect degeneracy is never attained in practice. Many methods have been developed for tuning MEMS post-resonator gyroscopes. For example [1] and [2] use adaptive and closed-loop methods, while [3] changes the frame of the pick-off signal. Our approach of gyro tuning is achieved through an electrostatic biasing approach [11]. This approach consists of applying bias voltages to built-in tuning pads to electrostatically soften the mechanical springs. Because of the time consuming nature of the tuning process when performed manually, in practice any set of

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bias voltages that produce degeneracy is viewed as acceptable at the present time. Thus a need exists for reducing the time necessary for performing the tuning operation, and for finding the optimally tuned configuration, which employs the minimal maximum tuning voltage.

This paper describes the application of evolutionary computation to this optimization problem. Our closed-loop methods used a fitness function for each set of bias voltages applied to the built-in tuning pads: the frequency split between the two modes of resonance of the MEMS gyroscope. Our closed-loop method, also called "switched drive-angle" method, is based on controlling the gyro in a closed-loop along one axis and measuring the resonance frequency along this axis at a given set of bias voltages, then swapping and driving the other axis, thereby extracting the resonant frequency of both axes. An evolutionary algorithm is then applied iteratively to modify the bias voltages until the resonant frequency of each axis is equal. A major advantage of this closed-loop approach is that the resonant frequencies can be extracted quickly (~1 second) as compared to the open-loop control system [14], which takes two orders of magnitude longer. The design of the closed-loop control approach is realized on an FPGA with augmented portability for future designs and implementations.

This paper is organized such that Section 2 describes the mechanics of the MEMS micro-gyro, Section 3 describes the closed-loop hardware platform and the results of our preliminary experiments, and Section 4 describes future directions and summarizes the project results..

2. Test Setup for Gyro Tuning

The mechanical design of the JPL MEMS micro-gyro can be seen in Figure 1. The JPL/Boeing MEMS post resonator gyroscope (PRG), is a MEMS analogue to the classical Foucault pendulum. A pyrex post, anodically bonded to a silicon plate, is driven into a rocking mode along an axis (labeled as X in Figure 1) by sinusoidal actuation via electrodes beneath the plate. In a rotating reference frame the post is coupled to the Coriolis force, which exerts a tangential "force" on the post. Another set of electrodes beneath the device senses this component of motion along an axis (labeled as Y in the figure) perpendicular to the driven motion. The voltage that is required to null out this motion is directly proportional to the rate of rotation to which the device is subjected and the voltage scale is reduced proportionally to the frequency split between the two modes of resonance. A change in capacitance occurs as the top plate vibrates due to the oscillating gap variation between this plate and the electrodes underneath. This change in capacitance generates a time-varying sinusoidal charge that can be converted to a voltage using the relationship V=Q/C. The post can be driven around the drive axis by applying a time-varying voltage signal to the drive petal electrodes labeled D1-, D1+, D1in-, and D1in+ in Figure 1. Because there is symmetry in the device, either of the two axes can be designated as the drive axis. Each axis has a capacitive petal for sensing oscillations as well; driving axis: labeled S1+ and S1- in Figure 1, sensing axis: labeled S2+ and S2- in Figure 1. The micro-gyro has additional plates that allow for electrostatic softening of the silicon springs, labeled B1, BT1, B2, and BT2 in Figure 1. Static bias voltages can be used to modify the amount of softening for each oscillation mode. In an ideal, symmetric device, the resonant frequencies of both modes are equal; however, unavoidable manufacturing imperfections in the machining of the device can cause asymmetries in the silicon structure of the device, resulting in a frequency split between the resonant frequencies of these two modes. The frequency split reduces the voltage scale used to measure the rate of rotation to which the device is subjected, and thus the sensitivity for detection of rotation is decreased. By adjusting the static bias voltages on the capacitor plates, frequencies of resonance for both modes are modified to match each other; this is referred to as the tuning of the device using an electrostatic biasing approach [11].

In order to extract the resonant frequencies of the vibration modes, there are two general methods: 1) open-loop and 2) closed-loop control [9]. In an open-loop system, we are measuring the frequency response along the drive axis over a 50Hz band and extract from the measurement the frequency split [14]. A faster method is a closed-loop control, whereby the gyro is given an impulse disturbance and is allowed to oscillate freely between the two resonance frequencies, using a hardware platform to control the switch of the drive-angles.

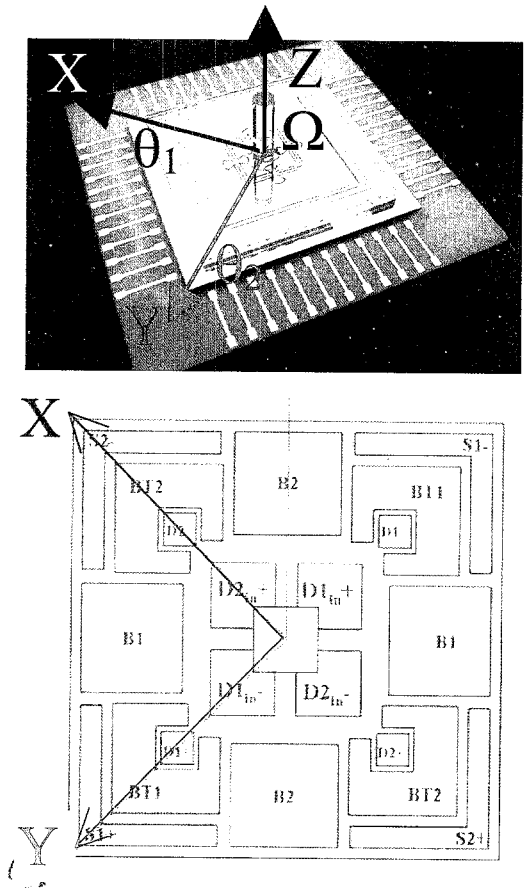


Figure 1. A magnified picture of the JPL MEMS micro-gyro with sense axis Y (S2-, S2+ electrodes used to sense, D2-, D2+, D2in- and D2in+ used to drive along the sense axis) and drive axis X (D1-, D1+, D1in- and D1in+ used to drive, S1-, S1+ electrodes used to sense along the drive axis) and the electrodes used for biasing (B1, B2, BT1, BT2).

3. Overview of Algorithm

As with most prototype sensor development, the JPL/Boeing MEMS post-resonator gyroscope is custom-built and hand-tuned for optimal performance. Many methods have been developed for tuning MEMS post-resonator gyroscopes. For example [1] and [2] use adaptive and closed-loop methods while [3] changes the frame of the pick-off signal. Our approach of gyro tuning consists of adjusting 4 bias voltages between -60V and +15V on capacitor plates to reduce the frequency split. Our approach can be seen as an optimization problem where the value to minimize is the difference between two frequencies and the parameters are the four bias voltages. We propose *genetic algorithms* used for different space applications [4]- to optimize the values of bias voltages applied to built-in tuning pads on the MEMS post-resonator gyroscope.

Genetic algorithms (GA), first introduced by John Holland and his colleagues [5], are search algorithms based on the mechanics of natural selection found in biology. GAs are theoretically and empirically proven to provide robust search in complex parameter spaces. Furthermore, they are not fundamentally limited by restrictive assumptions about the search space such as continuity and existence of derivatives.

The standard GA proceeds as follows. A possible solution of a given problem is encoded as a finite string of symbols, known as a genome. An initial population of the possible solution called individuals is generated at random or heuristically. At every evolutionary step, known as a generation, the individuals in the current population are decoded and evaluated according to some predetermined quality criterion, referred to as the fitness. To form the next generation, parents are selected with a probability proportional to their relative fitness. This ensures that the expected number of times an individual is chosen is approximately proportional to its relative performance in the population. Thus, low-fitness ones are more likely to disappear.

The parent selection process is followed by genetically inspired operators to form offspring. The most well known operators are mutation and crossover. The mutation operator is introduced to prevent premature convergence to local optima by randomly sampling new points in the search space with some probability. Crossover is performed with a different probability between two selected parents, by exchanging parts of their genomes to form two offspring. In its simplest form, substrings are exchanged after a randomly selected crossover point. This operator tends to enable the evolutionary process to move toward promising regions of the search space. Genetic algorithms are stochastic iterative processes that are not guaranteed to converge. The termination condition may be specified as some fixed, maximal number of generations or as the attainment of an acceptable fitness level.

To reduce the number of evaluations of potential solutions we used a modified GA called Dynamic Hill Climbing introduced by Yuret et al. [6]. We start with a potential solution represented by a point in a four dimensional search space that is easiest to implement (from the hardware standpoint). We then use a hill climbing method to find a best neighboring point and continue until we do not find any neighboring points with a better fitness. Then we decrease the search radius to zoom in on the optimum. If the found optimum is of unacceptable fitness, a new starting point is found by computing a location that is farthest in the search space from all local optima already found. We repeat the process until a desirable optimum is found. The algorithm has allowed reducing the number of evaluations by one order of magnitude compared to the traditional GA.

4. HARDWARE PLATFORM

The principle of "switched drive-angle" electrostatic biasing is based on measuring the resonance frequencies of the drive axis at a given set of bias voltages then swapping and driving the other axis, thereby extracting the resonant frequencies of both axes. An algorithm is then applied iteratively to modify the bias voltages until the resonant frequency of each axis is equal. A major advantage of this closed-loop approach is that the resonant frequencies can be extracted quickly (~1 second) as compared to the open-loop control system, which takes two orders of magnitude longer. The design of the electrostatic biasing approach is realized on an FPGA with augmented portability for future designs and implementations.

Control of the MEMS Micro-gyro

The "switched drive-angle" approach requires a closed-loop control whereby the gyro is given an impulse disturbance and is allowed to oscillate freely. This so-called "pinging" of the vibration mode allows the gyroscope to immediately settle to its natural frequency. The corresponding frequency, F1, is measured from the sensing plate under the drive axis X. Because the device is relatively symmetric, the drive and sense axes are swapped and the other mode is pinged to get F2. The difference in the frequencies, i.e., frequency split, is determined very quickly using this technique, about 1.5 seconds, roughly 50 times faster than from the open-loop control method. This ability to quickly swap the drive axis with the sense axis is a feature of our FPGA Gyro Digital System (GDS).

The circuitry of the closed-loop control system includes a drive loop and a sense re-balance loop [3]. The drive loop takes the input from the "drive sense" petal (S1-, S1+ electrodes along the drive axis), and outputs the forcing signal to the "drive-drive" petal electrodes (D1-, D1+, D1in- and D1in+ electrodes along the drive axis). The sense rebalance loop receives input from the "sense-sense" petal (S2-, S2+ electrodes along the sense axis), and forces or rebalances the oscillations back along the drive axis with a forcing signal to the "sense drive" (D2-, D2+, D2in- and D2in+ electrodes). The magnitude of this forcing function in the rebalance loop is related to the angular rate of rotation. The closed-loop control has also several scaling coefficients, denoted as Ki, which allow for a mixing of the sensed signals from both axes and a swapping of the drive- and sense-axis, thus permitting the tuning algorithm to measure the resonance frequency along the X- or Y-axis, or, indeed, any axis between X and Y [9].

The drive loop implements an Automatic Gain Control (AGC) loop combined with finite impulse response (FIR) filters. Because the amplitude of the freely oscillating drive axis will naturally decay, the AGC is implemented in a way to lightly drive or damp, depending on the circumstance, the drive axis so that the amplitude of the driven signal is constant and the gyroscope is maintained in an oscillation mode at the natural frequency. The optimal parameters of the FIR filters and the AGC loop to maintain the oscillation of the gyroscope have been determined by the UCLA team using a DSP measurement system and a UCLA MatLab modeling tool [12].

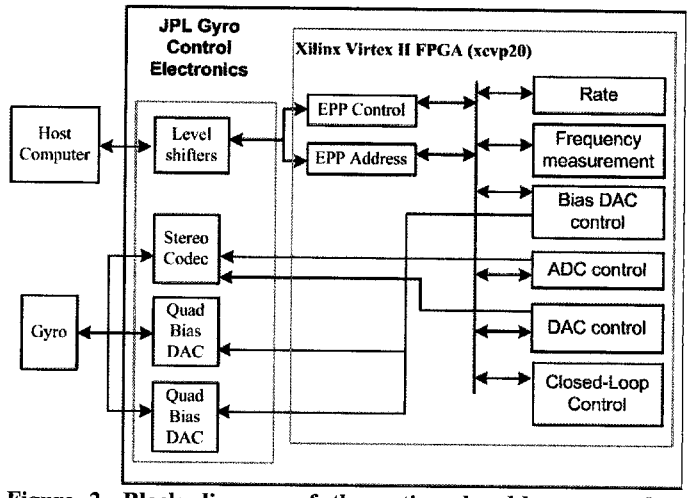


Figure 2. Block diagram of the entire closed-loop control system.

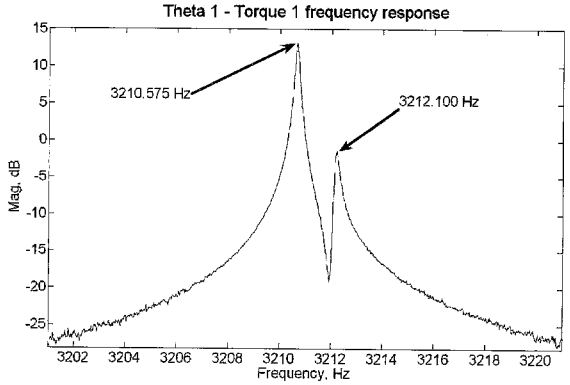
Gyro Digital System (GDS)

The system used to implement the control, operation, and observability of the micro-gyro is referred to as the Gyro Digital System (GDS). Figure 2 illustrates the implementation of the analog and digital systems used to control the micro-gyro. The key circuit elements that allow proper operation of the micro-gyro include the audio codec (Stereo Digital to Analog Converter DAC), high voltage Analog to Digital Converters (ADCs), IEEE-1294 Enhanced Parallel Port (EPP) interface replaced by a Universal Asynchronous Receiver/Transmitter (UART) serial interface, frequency measurement and the Digital Signal Processor (DSP) functionality integrated into a Xilinx Virtex II FPGA.

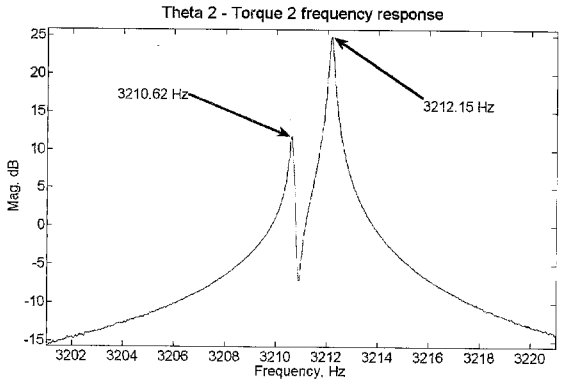
The audio codec is used to translate the analog sensing signals for both the drive and the sense axes. Its stereo capabilities allow for two inputs and two outputs. The high-voltage DACs are utilized for the setting of the electrostatic bias voltages on the gyro-scope, which range from +15V to -60V. The parallel port interface allows for user input/output capabilities. The user can configure the coefficients for the finite impulse response (FIR) filters along with the scaling coefficients (K1 through K8) and automatic gain control (AGC) proportional integral (PI) coefficients (Kp and Ki). The codec is configured through this interface as well.

5. RESULTS OF EVOLUTIONARY COMPUTATION

Using this FPGA digital control system, the micro-gyro was operated for a period of several hours and provided a frequency measurement that was stable to 1 mHz.



(a)



(b)

Figure 3. Bode magnitude of the experimental frequency response data for a non-tuned MEMS micro-gyroscope (B1=B2=BT1=BT2=0V). (a) drive axis on the axis X. (b) drive axis on the axis Y

This FPGA system has been tested in the mode where the drive- and sense-axes are swapped. We had before hand performed experiments using a DSP platform controlled by a Simulink environment running on a PC that demonstrates the feasibility of the closed-loop approach. In Figure 3 we show the frequency response of a non-tuned MEMS gyroscope (B1=B2=BT1=BT2=0V) with two peaks for each of the resonance frequencies when the drive axis is along axis X (Fig 4a) and when the drive axis is along axis Y (Fig 4b). Using a closed-loop control, the UCLA team was able to find the correct AGC and FIR filter parameters to maintain the gyro in an oscillating mode at the natural frequency. The DSP platform measured the frequency of both modes by swapping the drive and sense axis (F1=3210.62Hz and F2=3212.15Hz) as shown on Figure 3. Keeping the value of the AGC and FIR parameters constant and changing the value of the DC bias voltage, we were able to maintain the gyro in an oscillation mode and to extract both resonance frequencies, which have changed due to the update DC bias voltage.

The next step is to couple the FPGA frequency measurement with the genetic algorithm (GA) and the simulated annealing (SA) running on the PC. The ultimate goal is to implement the GA and the SA on the microprocessor (Power PC) integrated into a FPGA.

Quadrature Signal

Measuring the frequency split has turned out to be nontrivial; the post does not appear to always resonate purely along one axis. This means that the measured frequency split is not necessarily accurate. It appears that when the two peaks of the gyro's frequency response curve are of equal amplitude (usually less than one decibel) (Figure 4), the gyro resonates at one of the peak or is swapping between the two peak frequencies, and does not change frequency when the drive axis is swapped. These situation need to be detected and avoided.

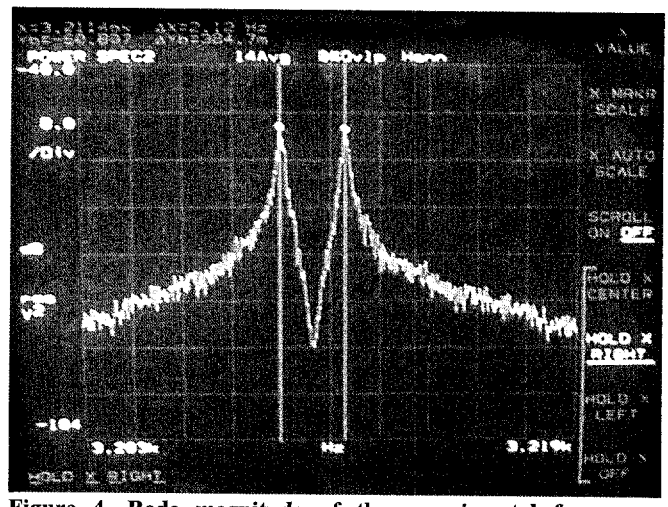


Figure 4. Bode magnitude of the experimental frequency response data for a non-tuned MEMS micro-gyroscope when both amplitude at the resonance frequency is equal.

The angle of vibration with respect to the axis X (driven axis) can be derived from a quadrature signal, which consists of the signal from the drive axis multiplied by the signal from the sense axis, phase shifted 90 degrees. Preliminary results indicate that when the difference between quadrature values (measured driving one axis, then driving the other axis) is large enough, the measured frequency split is fairly accurate (Figure 5). The fitness function for the evolutionary algorithm was modified to reject generations exhibiting quadrature values that are too close to each other. Preliminary testing has resulted in frequency splits less than 100 mHz, with the requirement that the absolute difference in quadrature values was at least 0.3. The goal is 50 mHz, which might be reachable by tweaking which generations are rejected.

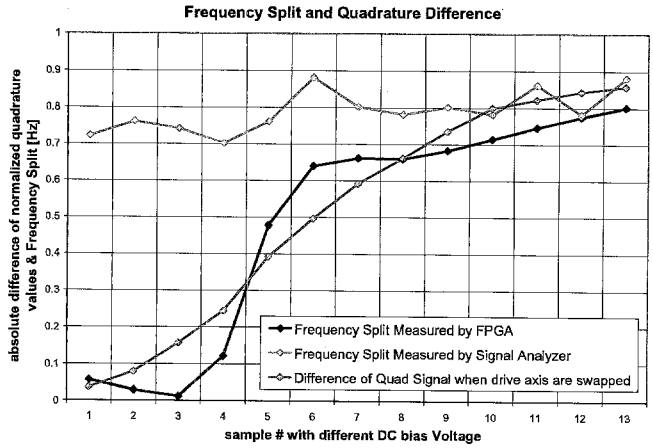


Figure 5. Correlation between the frequency split measured by the FPGA and the absolute difference of the normalized quadrature average when the drive axis is swapped between axis X and Y. The frequency split measured by the FPGA is identical to the one measured by the signal analyzer when the absolute difference of the quadrature signal is large

Results of the Dynamic Hill Climbing

We were able also to fine-tune the MEMS post-resonator gyroscope within 30 minutes fully automatically using a genetic related algorithm: dynamic hill climbing. Figure 6 shows the progress of the optimization algorithm aimed at minimizing the frequency split. Each evaluation is a proposed set of bias voltages. Our optimization method only needed 50 evaluations (30 min) to arrive at a set of bias voltages that produced a frequency split of less than 100mHz.

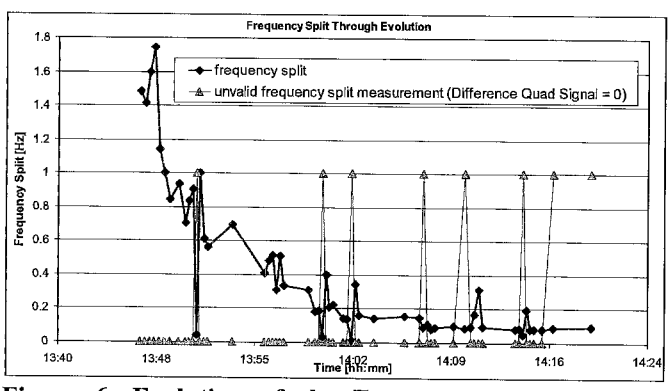


Figure 6. Evolution of the Frequency split through Evolution. Red marks with value 1 show when the frequency split measurement was ignored due to a similar value of the quadrature signal.

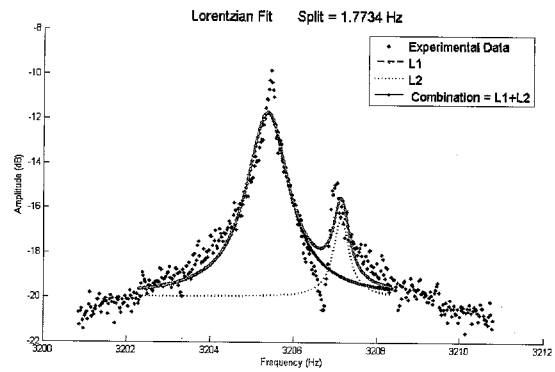


Figure 7. Frequency Response (12Hz band) before tuning using the genetic algorithm. The Frequency Split is 1773 mHz. The Y axis is measured in dB. The initial values of the four bias voltages are: B1 = 0.00V BT1 = 0.00V B2 = 0.00V BT2 = 0.00V.

Figures 7 and 8 show the frequency response for the unbiased micro-gyro respectively before and after tuning using the dynamic hill climbing.

For this run, after optimization of the bias voltages (Figure 8) in less than 10 min, the frequency split has been minimized to less than 15mHz and the two peaks are indistinguishable on an HP spectrum analyzer at 15mHz/division (12Hz span, 800 points) setting.

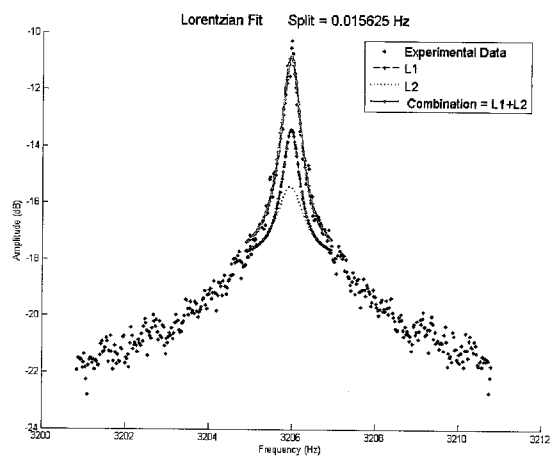


Figure 8. Frequency Response (12Hz band) after tuning using the genetic algorithm. The Y axis is measured in dB. The tuning Frequency Split is 15mHz. The optimized values of the four bias voltages are: B1 = -25V BT1 = 21V B2 = 11V BT2 = -9V.

6. SUMMARY

The tuning method for MEMS micro-gyroscopes based on evolutionary computation shows great promise as a

technology to replace the cumbersome, manual tuning process. We demonstrated, using a "switched drive-angle" measurement that we can, for the first time fully automatically, obtain a four times smaller frequency split at a tenth of the time, compared to human performance. We also showed that the "switched drive-angle" system has the option of swapping the drive- and sense-axes, thus decreasing the time required for tuning by more than a factor of fifty compared to the open-loop approach [14]. Additionally, a future design will include a microprocessor on-chip to allow for in-situ re-tuning of the MEMS micro-gyroscope if there is an unexpected change in the behavior due to radiation, temperature shift, or other faults.

The novel capability of fully automated gyro tuning, integrated in a single device next to the gyro, would enable robust, low-mass and low-power high-precision Inertial Measurement Unit (IMU) systems to calibrate themselves autonomously during ongoing missions, e.g., Mars Ascent Vehicle.

7. ACKNOWLEDGEMENTS

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BIOGRAPHY

Didier Keymeulen *received the BSEE, MSEE and Ph.D. in Electrical Engineering and Computer Science from the Free University of Brussels, Belgium in 1994. In 1995 he was the Belgium laureate of the Japan Society for the Promotion of Science Post Doctoral Fellowship for Foreign Researchers. In 1996 he joined the computer science division of the Japanese National Electrotechnical Laboratory as senior researcher. Since 1998, he is member of the technical staff of JPL in the Bio-Inspired Technologies Group. At JPL, he is responsible for the applications of the DoD and NASA projects on evolvable hardware for adaptive computing that leads to the development of fault-tolerant electronics and autonomous and adaptive sensor technology. He served as the chair, co-chair, program-chair of the NASA/DoD Conference on Evolvable Hardware. Didier is a member of the IEEE.*

Luke Breuer *is a Caltech student and intern at NASA's Jet Propulsion Laboratory, Pasadena, CA.*

Michael I. Ferguson *is a member of the Technical Staff in the Bio-Inspired Technologies and Systems group. His focus is on evolutionary algorithm application to VLSI design and arithmetic algorithms. He is currently working on the application of GA to tuning MEMS micro gyros. His other projects include evolution of digital and analog circuits intrinsically and extrinsically using a variety of methods. He was the Local Chair of the 2003 NASA/DoD Conference on Evolvable Hardware. He received a M.S. in Computer Science from University of*