

Tuning of MEMS devices using Evolutionary Computation and Open-Loop Frequency Response.

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Abstract— We propose¹² a tuning method for 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. The tuning method was tested for the second generation JPL/Boeing Post-resonator MEMS gyroscope using the measurement of the frequency response of the MEMS device in open-loop operation.

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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 and power efficiency. Towards this end, under current development at JPL are several different designs for high performance, small mass and volume, low power MEMS gyroscopes. The accuracy with which the rate of rotation of gyroscopes can be determined depends crucially on the properties of the resonant structure. It is 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.

The sensitivity of the MEMS gyroscope is maximized when the resonant frequencies of the two modes of freedom of the MEMS gyroscopes are identical. Symmetry of construction

is necessary to attain degeneracy. However, despite a symmetric design, perfect degeneracy is never attained in practice. Tuning of the gyros into degeneracy is achieved through application of bias voltages on 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 bias voltages that produce degeneracy is viewed as acceptable at the present time. A need exists for reducing the time necessary for performing the tuning operation, and for finding the optimal tuned configuration, which employs the minimal maximum tuning voltage.

This paper describes the application of evolutionary computation to this optimization problem. Our method used as fitness function for each set of bias voltages applied to built-in tuning pads, the evaluation of the frequency split between the two modes of resonance of the MEMS gyroscope. Our evaluation proceeds in two steps. First it measures the frequency response using a dynamic signal analyzer. Second it evaluates the frequency of resonance of both modes by fitting Lorentzian curves to the experimental data. The process of setting the bias voltages and the evaluation of the frequency split is completely automated by computer that controls signal analyzer and power supplies through General Purpose Interface Bus (GBIB). Our method has demonstrated that we can obtain a frequency split of 52mHz in one hour compared with 200mHz obtained manually by humans in several hours.

2. OVERVIEW OF ALGORITHMS

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 [8] and [9] use adaptive and closed-loop methods while [10] changes the frame of the pick-off signal. As explained in section 3, 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

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minimize is the difference between two frequencies and the parameters are the four bias voltages. We propose two *stochastic optimization algorithms - genetic algorithms and simulated annealing* used for different space applications [6]- to optimize the values of bias voltages applied to built-in tuning pads on the MEMS post-resonator gyroscope.

Genetic Algorithms

Genetic algorithms (GA), first introduced by John Holland and his colleagues [1], are search algorithms based on the mechanics of natural selection and sexual reproduction. 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. [7]. 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.

Simulated Annealing Algorithms

Simulated annealing (SA) is a widely used and well-established optimization technique especially for high-dimensional configuration spaces [2,3]. The goal is to minimize an energy function or fitness function E (in the following the frequency split of the MEMS micro-gyro), which is a function of N variables (the 4 correction voltages for the MEMS micro-gyro), with N being usually a large number. The minimization is performed by randomly changing the value of one or more of the N variables and reevaluating the energy function E . Two cases can occur: 1) the change in the variable values results in a new, lower energy function value; or 2) the energy function value is higher or unchanged. In the first scenario the new set of variable values is stored and the change accepted. In the second scenario, the new set of variable values is only stored with a certain likelihood (Boltzmann probability, including an annealing temperature). This ensures that the overall optimization algorithm does not get stuck in local minima too easily (greedy downhill optimization). The annealing temperature directly influences the Boltzmann probability by making it less likely to accept an energetically unfavorable step, the longer the optimization lasts (cooling schedule). Then the overall procedure is repeated until the annealing temperature has reached its end value, or a preset number of iterations has been exceeded, or the energy function E has reached an acceptable level.

3. TEST SETUP FOR GYRO TUNING

Both stochastic optimization methods have been implemented on a dedicated, JPL/Boeing-specific hardware platform, which is described in the following sections.

Mechanism of the JPL MEMS Microgyro

The mechanical design of the JPL MEMS microgyro can be seen in Figure 1. There are two posts on the microgyro, one is affixed to the top plate and the other (not shown) is affixed to the base plate. In order for the gyroscope to operate, the silicon posts (center) must oscillate around an axis (i.e. X as labeled in the figure). Because the oscillations are driven around this axis, it is called the drive axis. Rotation Ω around the Z -axis will cause Coriolis forces that couple vibrations from the drive axis to the orthogonal axis, called the sense axis (i.e. Y as labeled in the figure). The vibrations coupled to this sense axis are related to the angular rate Ω of rotation around the Z -axis. The top

post is affixed to sixteen capacitive petals (called a resonator) that are suspended above a micro-machined base plate by four outer silicon torsional springs. The upper and lower plates are set 10 μ m apart. Oscillations cause a variation of capacitance to occur in the internal structure of the device. This change in capacitance generates a time-varying sinusoidal charge that can be converted to a voltage using the relationship $V=Q/C$. The posts 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 the figure. The microgyro has additional plates that allow for electrostatic damping labeled B1, BT1, B2, and BT2 in Figure 1. Static bias voltages can be used to modify the amount of damping to each oscillation mode. In an ideal, symmetric device, the resonant frequencies of both modes are equal; however, manufacturing imperfections in the machining of the device can cause dissimilarities in the device's silicon structure. Because of these imperfections, a non-degeneracy in the post's modes of oscillation exists, which manifests itself as a difference in the resonant frequencies around each axis called the *frequency split*. The frequency split causes the reduction of the coupling by Coriolis force between the driven motion in one modal direction and the other modal direction and thus reduces the sensitivity of the measurement of the rate of inertial rotation the device is undergoing. 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.

In order to extract the resonant frequencies of the vibration modes, there are two general methods: 1) open-loop and 2) closed-loop control [5]. 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. 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 controlling the switch of the drive-angles [4].

Instrumentation Platform

The measurement consists of exciting the drive axis with a sine wave at a given frequency and measuring the resulting amplitude. This is done repeatedly through the frequency spectrum. Because of cross-coupling between the different axes, two peaks in the amplitude response will appear at two different frequencies, showing the resonant frequencies of both axes as shown in Figure 7. This takes approximately 1.4 minutes to complete using our instrumentation platform and must be done at least three times to average out noise.

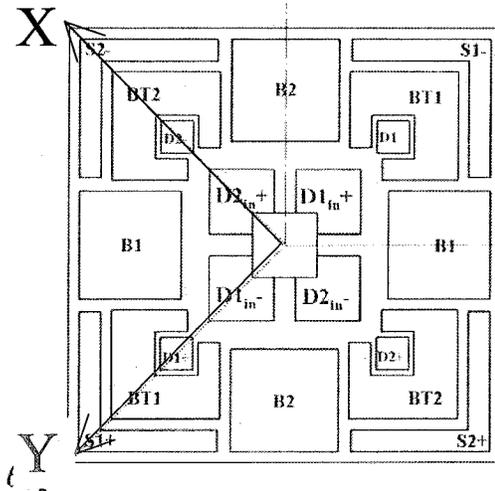
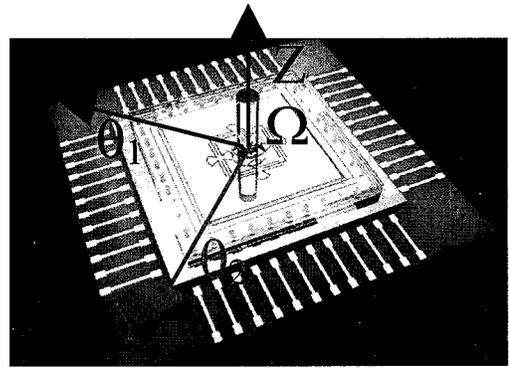


Figure 1. A magnified picture of the JPL MEMS microgyro with sense axis Y (S2-, S2+ electrodes used to sense, D2-, D2+, D2in- and D2in+ used to drive along the sense axis) and drive axis X (D1-, D1+, D1in- and D1in+ used to drive, S1-, S1+ electrodes used to sense along the drive axis) and the electrodes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

The platform includes one GPIB programmable power supply DC voltage, a GPIB signal analyzer to extract frequency responses (from 3.3kHz to 3.35kHz) of the gyro in open-loop, and a computer (PC) to control the instruments and execute the optimization algorithms. The supply DC voltage is controlling the static bias voltages (connected to the plate B1, BT1, B2, and BT2 in Figure 1) that are used to modify the amount of damping to each oscillation mode. The GPIB signal analyzer generates a sine wave with a variable frequency (from 3300 Hz to 3350 Hz and a step of 62.5 mHz – 800 points, 50Hz span) on the drive electrode (D1-, D1+, D1in- and D1in+ in Figure 1) and measures the response signal on the sense electrode (S1-, S1+ in Figure 1) along the drive axis X.

A PC is running an instrument control tool, a measurement tool, and an evolutionary computation tool. The instrument control software sets up the static bias voltages using the GPIB power supply DC voltage and measures the frequency

response along the X axis using the GPIB signal analyzer as shown in Figure 2. The measurement tool software calculates the frequency split using peak fitting algorithms. Finally the evolutionary algorithm software determines the new DC bias voltages from the frequency split. This procedure is repeated until a satisfactory frequency split is obtained.

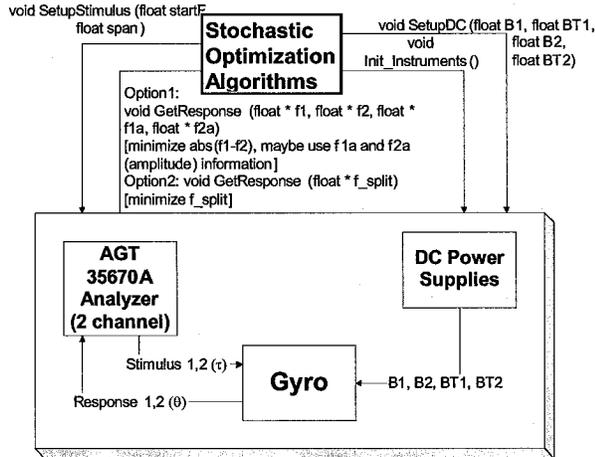


Figure 2. Software interface for the Simulated Annealing and GA to the Instrumentation Platform using a PGIB programmable power supply DC voltage and a signal analyzer. The Simulated Annealing and GA/Hill Climbing are running on a PC, which controls the bias voltages and receives the frequencies of both modes of resonance.

4. EVALUATION OF THE FREQUENCY SPLIT

We have developed a method to extract the peak from the frequency response using a peak fitting algorithm based on a model of the transfer function of the MEMS microgyro [5]. The transfer function $H(s)$ for a single input- single output (SISO) system, modeling the gyro behavior, is described in Equation 1. The transfer function relates the angle velocity of the drive axes $\dot{\theta}_1$ and the torque in the drive axes τ_1 . The constants in the equation are as follows:

- ω_d : natural resonance of the sensor axis' driving mode
- Q_d : quality factor depends on the spring constant
- J_i : symmetric moments of inertia around the X and Y axes

$$H(S) = \frac{\left(\frac{1}{J_i}\right)S}{S^2 + \frac{\omega_d}{Q_d}S + \omega_d^2} \quad (1)$$

The SISO model is approximated by the Lorentzian function shown in Equation 2 and illustrated in Figure 3. It is

characterized by having a very sharp narrow peak with most of the intensity of the peak located in the tails (or “wings”), extending to infinity (Figure 3).

$$f(x) = \frac{H}{4 \left(\frac{x-x_0}{W}\right)^2 + 1} \quad (2)$$

where X_0 = Peak Position, H = Peak Height, W = Full width at Half Height

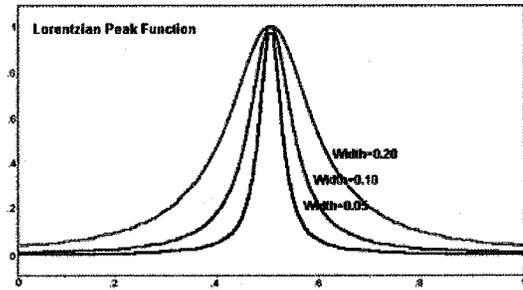


Figure 3. Lorentzian functions with different values used to approximate the transfer function of a SISO system, modeling the MEMS microgyro behavior.

The objective is to fit the sum of two Lorentzian functions to the frequency response experimental data as illustrated in Figure 4. We can then calculate the frequency split between the two modes of resonance by measuring the difference of the peak locations of each Lorentzian function.

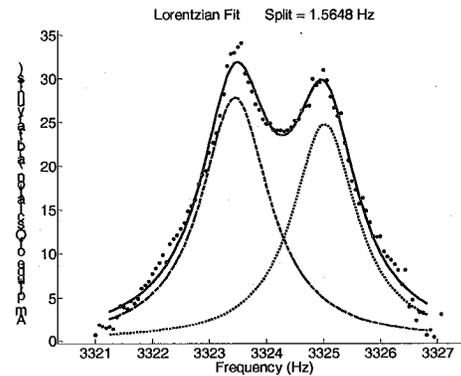


Figure 4. Fitting the sum of two Lorentzian functions to the frequency response experimental data. The green and blue curves are Lorentzian functions and the red curve is the sum of the two functions. The experimental data points are plotted in black.

Each Lorentzian function is completely described by 3 parameters as shown in Equation 2. To come up with two Lorentzian functions the sum of which best describes the experimental data, we have to optimize a total of 6 parameters.

Lorentzian 1: location (L1), width (W1), height (H1)

Lorentzian 2: location (L2), width (W2), height (H2)

We have used the Chi square statistic to measure the agreement between *actual/experimental/measured* data and

calculated/Lorentzian model. The Chi Squared is calculated as follows:

$$\chi^2 = \frac{\sum_{i=0}^n \left(\frac{\text{Actual}_i - \text{Calculated}_i}{\text{RMSNoise}} \right)^2}{(n-f)} \quad (3)$$

where *RMSNoise* is the estimated Root Mean Squared noise in the *actual* data. The variable *n* is the number of data points and *f* is the total number of variables in the Lorentzian model, i.e., 6.

The process of optimizing the 6 parameters in the Lorentzian model is described below:

Start at default values for all 6 variables.

Fixed an initial value for the step size

Loop until step size < threshold

1. Vary L1 and L2 by one step size while keeping all other parameters at their best values, calculate the Lorentzian model and evaluate the χ^2 of the fittest curves
 - a. Save values of L1 and L2 that produce lowest χ^2
2. Vary H1 and H2 one step size while using best parameters obtained so far, calculate the Lorentzian model and evaluate the χ^2 of the fittest curves.
 - a. Save values of H1 and H2 that produce lowest χ^2
3. Vary W1 and W2 one step size while using best parameters obtained so far, calculate the Lorentzian model and evaluate the χ^2 of the fittest curves.
 - a. Save values of W1 and W2 that produce lowest χ^2

Save the set of variable L1, L2, H1, H2, W1, W2 giving the best χ^2 .

If the variation of χ^2 from previous iteration is equal to zero then decrease step size

Once all six parameters are determined, frequency split is found by taking the difference between L1 and L2.

5. RESULTS OF EVOLUTIONARY COMPUTATION

The MEMS Micro-Gyro, developed by the MEMS Technology Group at JPL, is subject to an electro-static fine-tuning procedure, performed by hand, which is necessary due to unavoidable manufacturing inaccuracies. In order to fine-tune the gyro, 4 voltages applied to 8 capacitor plates have to be determined within a range of -60V to 15V respectively. The manual hand tuning took several hours and was able to obtain a frequency split of 200 mHz.

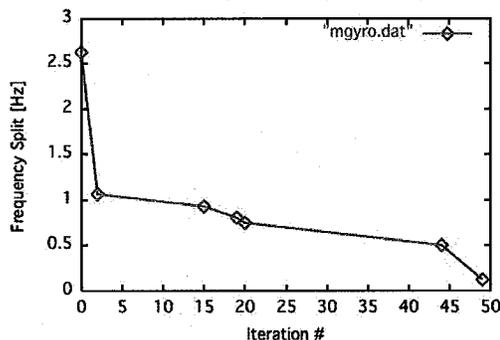
In order to fully automate the time-taking (on the order of several hours) manual fine-tuning process, we have established a hardware/software interface to the existing manual gyro-tuning hardware-setup using commercial-off-the-shelf (COTS) components described in section 4.

We developed and implemented two stochastic optimization techniques for efficiently determining the optimal tuning voltages and incorporated them in the hardware/software interface: a modified *simulated annealing related algorithm* and a modified *genetic algorithm with limited evaluation*.

Simulated Annealing Approach

We were able to successfully fine-tune both MEMS post-gyros and MEMS disk-resonating-gyros (a different gyro-design not discussed here) within one hour for the first time fully automatically. After only 49 iterations with the Simulated Annealing optimization algorithm we obtained a frequency split of 125mHz using a 50Hz span and 800 points on the signal analyzer for the MEMS post-gyroscope (Figure 5 top) and a frequency split of 250mHz within 249 iterations using a 200Hz span and 800 points on the signal analyzer for the MEMS disk-resonating-gyroscope (Figure 5 bottom). Both results are better than what can be accomplished manually.

MEMS Post Resonating Gyro Automated Tuning with Simulated Annealing



MEMS Disk Resonating Gyro Automated Tuning with Simulated Annealing

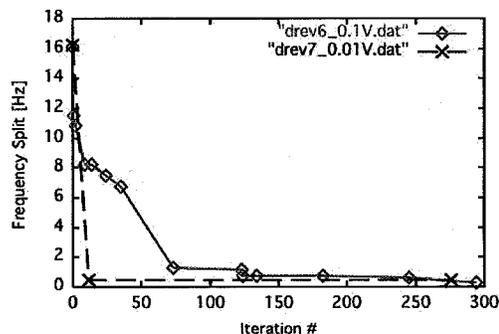


Figure 5. Frequency split as a function of Simulated Annealing Iterations: (top) for the MEMS post-gyro; (bottom) for the MEMS disk-resonating gyro.

Genetic Algorithm Approach

We were able also to fine-tune MEMS post-gyros within one hour 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 47 evaluations (51 min) to arrive at a set of bias voltages that produced a frequency split of less than 100mHz.

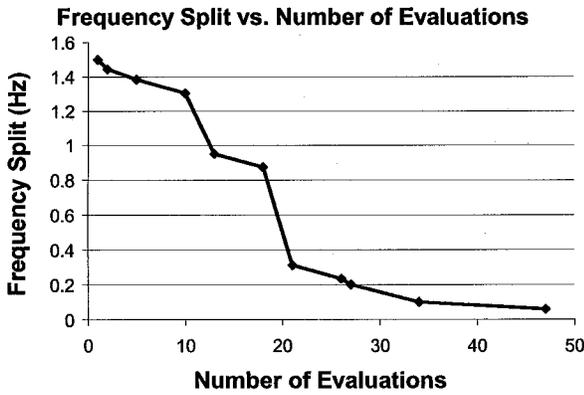


Figure 6. Frequency split as a function of Evaluation used by the Genetic Algorithm.

Figures 7 and 8 show the frequency response for the unbiased gyroscope respectively before and after tuning using the dynamic hill climbing and the peak fitting algorithm.

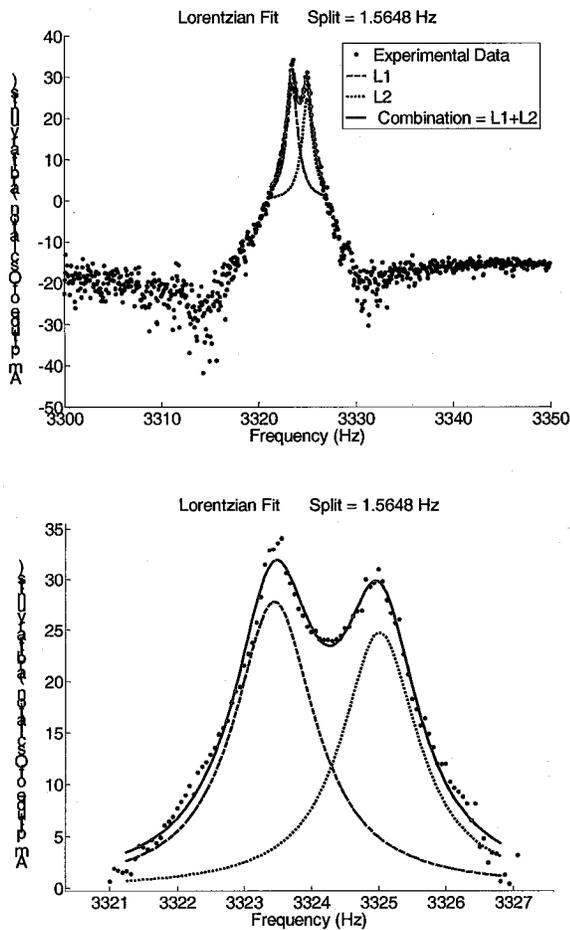


Figure 7. Frequency Response (top: 50Hz band, Bottom: 6Hz band) before tuning using the genetic algorithm. The Frequency Split is 1555mHz. The initial values of

the four bias voltages are: B1 = 14.00V BT1 = 14.00V B2 = 14.00V BT2 = 14.00V. The bottom picture shows a zoom of the frequency split over a 6Hz band.

After optimization of the bias voltages (Figure 8), the frequency split has been minimized to less than 100mHz and the two peaks are indistinguishable on an HP spectrum analyzer at 62.5mHz / division (50Hz span, 800 points) setting, which was used during the optimization process.

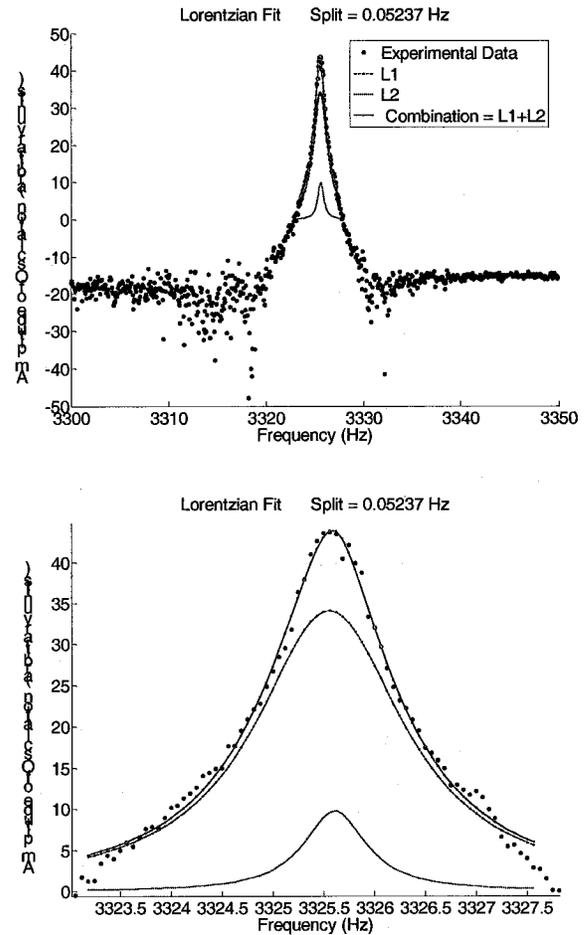


Figure 8. Frequency Response (top: 50Hz band, Bottom: 5Hz band) after tuning using the genetic algorithm. The tuning Frequency Split is 52mHz. The optimized values of the four bias voltages are: B1 = 4.00V BT1 = 4.00V B2 = 14.00V BT2 = -16.00V. The bottom picture shows a zoom of the frequency split over a 4Hz band.

The frequency split of 52mHz was verified using a higher resolution of the signal analyzer.

6. SUMMARY

The tuning method for MEMS gyroscopes based on evolutionary computation shows great promise as a technology to replace the cumbersome human manual tuning. We demonstrate that we can obtain a four times smaller frequency split at a tenth of the time. The novel capability of fully automated gyro tuning enables ultra-low mass and ultra-low-power high-precision Inertial Measurement Unit (IMU) systems to calibrate themselves autonomously during ongoing missions, e.g., Mars Ascent Vehicle. Our current effort is producing an even faster tuning algorithm based on a closed-loop measurement, which can be implemented on a single FPGA chip next to the gyro [4].

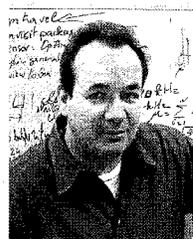
7. ACKNOWLEDGEMENTS

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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.



Wolfgang Fink is a Senior Researcher at NASA's Jet Propulsion Laboratory, Pasadena, CA, Visiting Research Assistant Professor of both Ophthalmology and Neurological Surgery at the University of Southern California, Los Angeles, CA, and Visiting Associate in Physics at the California Institute of Technology,

Pasadena, CA. His research interests include theoretical and applied physics, biomedicine, astrobiology, computational field geology, and autonomous planetary and space exploration. Dr. Fink obtained an M.S. degree in Physics from the University of Göttingen in 1993 and a Ph.D. in Theoretical Physics from the University of Tübingen in 1997. His work is documented in numerous publications and patents.



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 California at Los Angeles and a B.S. in Engineering Physics from the University of Arizona.



Chris Peay is an Engineer affiliated with NASA's Jet Propulsion Laboratory, Pasadena, CA. His current work is in the areas of control and readout electronics for MEMS vibratory gyroscopes (MVGs) and characterization testing and test

automation for MVGs. He received his BS degree in Electrical Engineering from the University of Utah in 1992 and is currently pursuing his MSECE degree at the Georgia Institute of Technology.



Richard Terrile created and leads the Evolutionary Computation Group at NASA's Jet Propulsion Laboratory. His group has developed genetic algorithm based tools to improve on human design of space systems and has demonstrated that computer aided design tools can also be used for automated innovation and design of

complex systems. He is an astronomer, the Mars Sample Return Study Scientist, the JIMO Deputy Project Scientist and the co-discoverer of the Beta Pictoris circumstellar disk. Dr. Terrile has B.S. degrees in Physics and Astronomy

from the State University of New York at Stony Brook and an M.S. and a Ph.D. in Planetary Science from the California Institute of Technology in 1978.

Karl Yee received his Ph.D. in Theoretical Physics from the University of California, Irvine in 1994. He is a senior researcher within the MEMS Technology group at NASA's Jet Propulsion Laboratory, and has 14 years of experience working on space related projects as an electronic packaging engineer and as a MEMS engineer. He is currently the task manager of JPL's Miniature Gyroscope project.



Boris Oks is an engineer in the Evolvable Hardware group at the Jet Propulsion Laboratory, Pasadena, CA.

His interests include: digital signal processing, machine learning algorithms and system optimization methods. Boris graduated from Cal State Northridge in 2002 with a BS in Computer Engineering. He is currently

pursuing an MS degree in EE. For 3 years prior to JPL, Boris worked for a small startup company developing software for home automation systems.