RIG CONCEPT TECHNICAL PROPOSAL

RFP NUMBER R-EP0044

A. Innovation in MEMS Gyroscopic Sensors

The goal of these investigations is to realize a microelectromechancial system (MEMS) implementation of a rate-integrating gyroscope. That is, an inertial sensor capable of producing a signal proportional to angular displacement. These sensors, while closely related to angular rate gyroscopes, present a challenge in terms of the characterization and control required for operation. However, the resulting devices will rival the size and cost of other silicon based implementations that are limited to the angular rate domain. Rate-integrating devices ("rate gyros") will prove highly desirable in applications that require the reduced cost and size associated with MEMS solutions while providing higher precision MEMS inertial measurement than previously available.

B. Background and Technical Objectives

MEMS Angular Rate Sensing Technology

There are a number of MEMS angular rate sensors available on the market today. One successful product family is the Analog Devices ADXRS family of sensors. This gyroscope is composed of a micromachined MEMS element and integrated CMOS chip packaged in less than $0.2cm^3$. The ADXRS610 has been utilized in a number of products designed and manufactured by MEMSense including inertial measurement units (IMU). One drawback to the use of these rate sensors is that they require some form of processing external to the chip in order to gain angular measurements precise enough for practical attitude determination. Often the gyro signals when combined with accelerometer data must be utilized with advanced processing techniques to enhance performance. Devices used in the MEMSense product line are characterized for systematic errors via temperature environment testing, cross sensitivity, and vibration. Temperature dependence information of the bias offset and sensitivity are gathered and compensating algorithms are determined for deployment in active compensation controls while errors due to vibration have been reduced via passive methods. It is important to emphasize that all bias errors lie in the rate domain and therefore cause even larger errors in the angular displacement domain after numerical integration has occurred. While rate sensors have seen great success in some applications, there use is limited due to the significant amount of complexity that is inevitably added to gain angular displacement information. There are higher precision MEMS alternatives: the BEI QRS11 is one of the highest performance MEMS angular rate sensors available today. This design is based on a MEMS quartz resonator referred to as a "tuning fork" gyro. The manufacturing of this device relies on much higher tolerances and is commensurately more expensive than its silicon counterparts. Compared to the ADXRS610 the QRS11 has a significantly larger package size which combined with increased cost makes it less desirable as a solution where the reduced size of silicon devices are highly desirable.

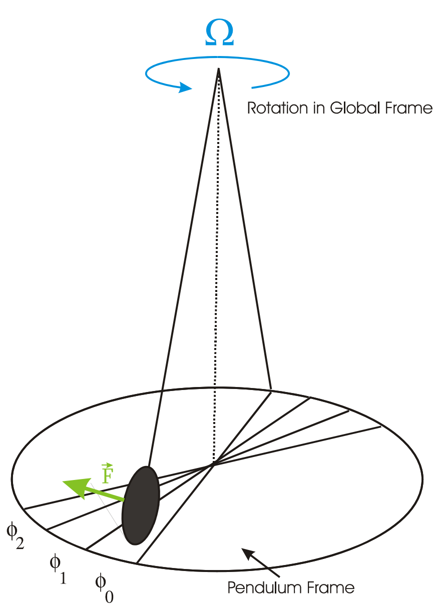

Figure 1: Foucault's Pendulum

Rate Integrating Gyroscopes

A rate-integrating gyroscope is proposed based on a mechanical resonator free to move in two dimensions. This is the same dynamic system observed in Foucault's pendulum experiment. A pendulum is set in motion with some period, T , and corresponding frequency, ω . Under the influence of gravity alone, and no losses due to friction, the pendulum will oscillate back and forth tracing the same path indefinitely. The system is now subjected to a constant rotation, Ω, external to the pendulum frame of reference. A force, *F* (Figure 1, in green) is observed, orthogonal to the plane of motion described by the motion of the pendulum called the Coriolis force. If the progress of the pendulum is noted at regular intervals it is found that the path the pendulum travels rotates a certain amount, ϕ_n , which is called the angle of precession. The equations describing this system are as follows:

$$\frac{F_x}{m} = \ddot{x} + \omega^2 x - 2\Omega\dot{y} \quad \textbf{Eq. 1}$$

$$\frac{F_y}{m} = \ddot{y} + \omega^2 y + 2\Omega\dot{x} \quad \textbf{Eq. 2}$$

The Coriolis components, $-2\Omega\dot{y}$ and $2\Omega\dot{x}$, have the form of velocity dependent damping terms coupled to the orthogonal axes and are directly proportional to the angular rate of rotation of the system This type of system is sometimes referred to as a vibrating member gyroscope when used to resolve the rotation of the global frame (a complete treatment of rate gyroscopes can be found in [2]). In the rate sensing system, the magnitude of this disturbing Coriolis force is measured and correlated to angular rate. In the rate integrating system the intent is to resolve gains in angular displacement as a function of the position and velocity of the mass.

A MEMS Rate Integrating Gyroscope

A vibrating member gyroscope can be realized via MEMS silicon manufacturing techniques that is the two-dimensional equivalent of the pendulum system. In the functionally 2-D system a mass will be coupled to an outer frame via silicon beams analogous to those found in MEMS actuators, accelerometers, and gyroscopes. Additional structures will constitute capacitive elements that will be used both as electromechanical actuators (“drives”) as well as sensing elements. Figure 2 shows a central mass connected to a frame via folded beam structures with intermediate capacitors. In this case the capacitors are composed of two elements, a fixed portion and a movable one.

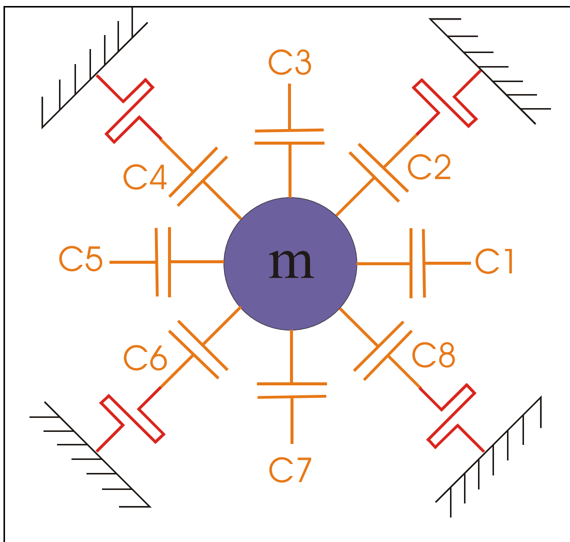

Figure 2: Functionality of the MEMSense RIG

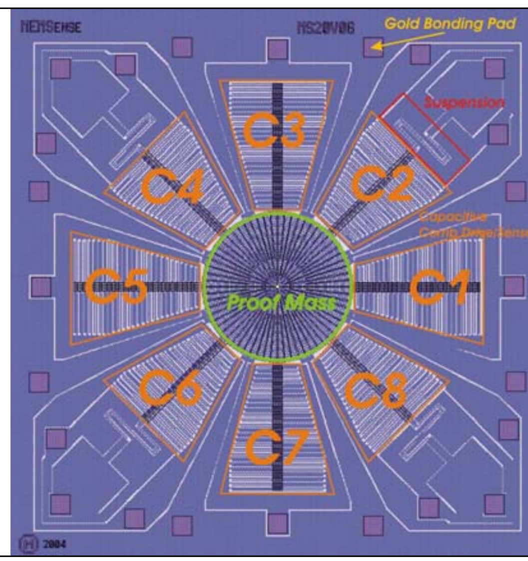

Figure 3: Layout of the Silicon Device

The silicon implementation has the functionality as shown in Figure 2. An example of a MEMSense design is shown in Figure 3. The capacitive elements are constructed from numerous interdigitated combs. Some typical values for candidate MEMS devices can be found in

.

Table 1: Typical Features of the MEMSense RIG

Feature Size	5μm
Hooke's Law Constant	6-800 N/m
Device Layer depth	50μm
Mass	0.023μg – 0.076μg
Natural Frequency	0.9 – 16 kHz
Area of Device	6.81mm^2

The range of parameters afforded by these parameter ranges allow exceptional flexibility in sensor system design in regards to bandwidth, sensitivity, and vibration rejection.

Dynamics of the RIG

In Cartesian coordinates we have the following system:

$$\ddot{x} + \omega^2 x - 2\Omega\dot{y} = 0 \quad \textbf{Eq. 3}$$

$$\ddot{y} + \omega^2 y + 2\Omega\dot{x} = 0 \quad \textbf{Eq. 4}$$

Where ω is the natural frequency of the spring-mass system and Ω is the rate of rotation about the *z*-axis. The general solution to this system involves orbital motion of the mass about the equilibrium position. To ease the analysis of the motion the system can be described via the orbital coordinates (Figure 4) a, b, ϕ, and θ. It can be shown [1] that

$$\phi = \frac{1}{2}\tan^{-1}\left[\frac{2(\omega^2 xy + \dot{x}\dot{y})}{\omega^2(x^2 - y^2) + (\dot{x}^2 - \dot{y}^2)}\right]. \quad \textbf{Eq. 5}$$

The precession angle , ϕ, is determined completely from the measurement of position and velocity of the proof mass. This fact suggests a convenient scenario where position and velocity are measured orthogonally in the MEMS device by appropriate detection systems and the progress of the mass precession is resolved thus revealing angular displacement in the global frame.

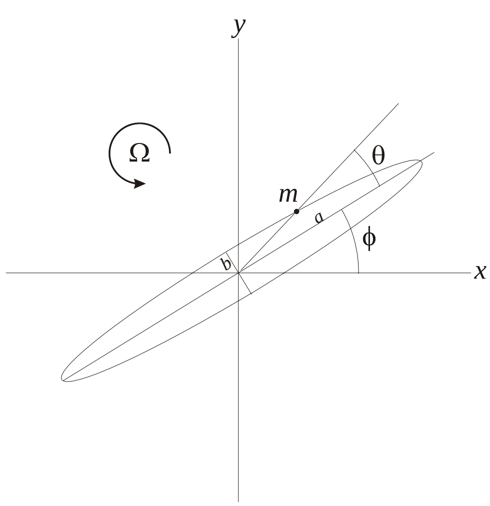

Figure 4: Orbital Coordinates for the Two Dimensional Oscillator

Calculation of System Energy

Operation of the RIG system relies on maintaining an average system energy and therefore compensating for losses to this energy. In the orbital coordinates the energy per unit mass can be shown to be

$$E = \frac{1}{2}\left(\omega^2 x^2 + \omega^2 y^2 + \dot{x}^2 + \dot{y}^2\right) \quad \textbf{Eq. 6}$$

and mass-normalized angular momentum is

$$H = x\dot{y} - y\dot{x} \quad \textbf{Eq. 7}$$

Where E and H are ideally constants. A major function of the control system is to maintain a nominal energy value in the system. The controls will compensate for losses while distinguishing the disturbing Coriolis forces via their characteristic spectral content.

Calculation of the Coriolis Response

The dynamics of the system follow the following equations in the presence of an external rotation rate, Ω:

$$\dot{a} = -\Omega b \sin 2\theta \quad \textbf{Eq. 8}$$

$$\dot{b} = \Omega a \sin 2\theta \quad \textbf{Eq. 9}$$

$$\dot{\phi} = \frac{2\Omega\left(b^2 \cos^2\theta - a^2 \sin^2\theta\right)}{a^2 - b^2} \quad \textbf{Eq. 10}$$

$$\dot{\theta} = \frac{-2\Omega ba \cos 2\theta}{a^2 - b^2} \quad \textbf{Eq. 11}$$

In the presence of a constant rotation we will have the following contribution to angular momentum

$$H_\Omega = \frac{\left(a^2 - b^2\right)}{2}\Omega \sin 2\omega\, t \quad \textbf{Eq. 12}$$

This contribution will have a unique signature in the frequency domain provided that due consideration has been made to the character of rotation frequencies to be measured relative to the frequency of the oscillator system. In other words, the devices must operate with carrier frequencies significantly higher than the range of angular displacements that the device is intended to measure. Returning to our pendulum as an analogy, we find that the frequency of earth's rotation ($\approx$1.2 x 10^{-5} Hz) is quite easily resolved by an vibratory oscillator operating at a frequency of $\approx$5 x 10^{-1} Hz (period of 2s) despite small losses due to friction present in a physical pendulum.

Driving and Sensing

Driving and sensing functions are carried out via capacitive comb structures (Figure 5) of which there are eight available in the concept design. As in other MEMS devices, drive and sensing functions make use of electrodynamic comb actuators that operate in the transverse mode. The physical layout of the comb elements are identical whether used for driving or sensing, but differ in the external electronics coupled to them.

Driving methods

External sources are used to impose carrier tones as well as variable frequency signals used to correct the dynamic behavior of the mass. There are a number of strategies in regards to what the carrier frequency shall be. Ultimately, bandwidth depends on the Q factor of the system which depends in part on fluid damping characteristics. There may be advantages to bandwidth depending on the careful choice of operating carrier frequency ω_q relative to the natural frequency ω of the system (e.g. $\omega_q >> \omega$).

Sensing

Sense combs are used to resolve position and velocity of the proof mass via attached capacitive pickoff systems at. This is accomplished via an electronic integrator cascaded upon a transimpedance amplifier. The transimpedance amplifier outputs the velocity dependent signal while the integrator produces the displacement signal. The MEMSense concept maximizes the amount of surface area available in the transverse mode which results in the truncated comb structures seen in Figure 5. This is to maximize the capacitance gradient (figure of merit) related to the comb structures and therefore allow superior sensing characteristics.

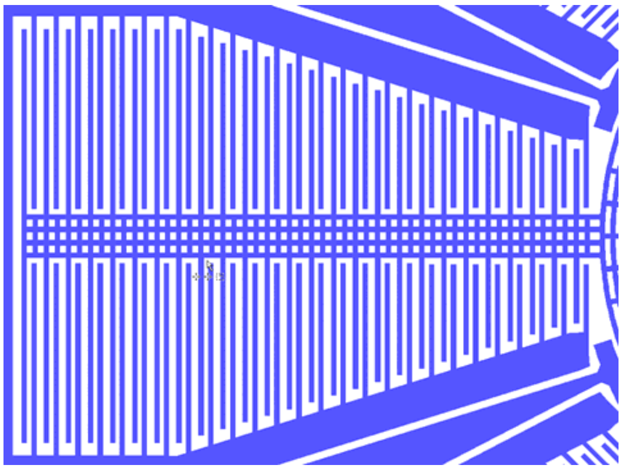

Figure 5: Capacitive Comb Drive

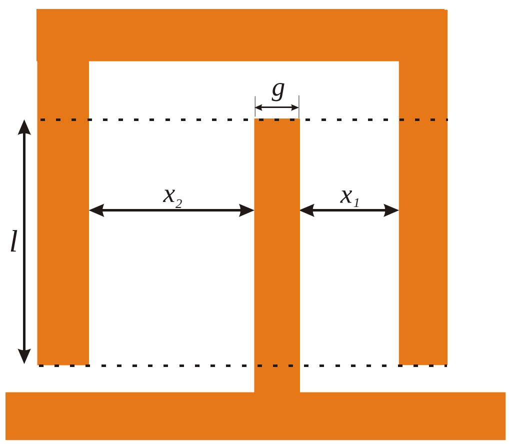

Figure 6: Detail of Interdigitated Combs

Table 2: Offset Comb Drive Parameters

parameter	units
g	feature size
x_1	inner gap
x_1	outer gap
l	comb overlap

Errors in the Rate Integrating Gyroscope System

Manufacturing imperfections and spring constant mismatch.

Global manufacturing defects affecting the geometry of the structures within the device will alter the characteristics of the suspension elements resulting in quadrature error. Quadrature error is caused by mismatch between the spring constant in one axis with the orthogonal axis. Any mismatch in stiffness, even small ones, lead to quadrature error. The presence of these errors result in the tendency of energy to be lost in one axis into the orthogonal one. Quadrature will have to be compensated for by the control system. The main feature of quadrature is the tendency for the precession angle to be “attracted” to a particular axis and therefore an erroneous precession angle

Fluid damping

Fluid damping will account for some portion of losses in the system. Evacuation of the MEMS device packaging that is placed in a hermetically sealed package could reduce damping effects significantly, but would add considerable cost per unit. A better alterative is to thoroughly characterize the damping forces during the prototyping phase and to make adjustments to the control system that allow for adequate compensation.

Deterministic Errors

In the use of MEMS devices for inertial measurement it is often necessary to compensate for variations in bias dependence on temperature or other environmental factors. Some of these deterministic errors may be compensated for on the chip level with sufficient characterization of the MEMS device. An additional feedforward system may be implemented to compensate for these variations as opposed to external compensation.

Control System

The constituent parts of the control system for the RIG will include an energy balance module, quadrature control compensation, as well as the driving and sensing elements. The architecture of the controls has the form of a typical feedback system.

Overview

The RIG control system can be divided into these subsystems:

1. Displacement angle calculator
2. Energy balance control
3. Quadrature control
4. State space conversion

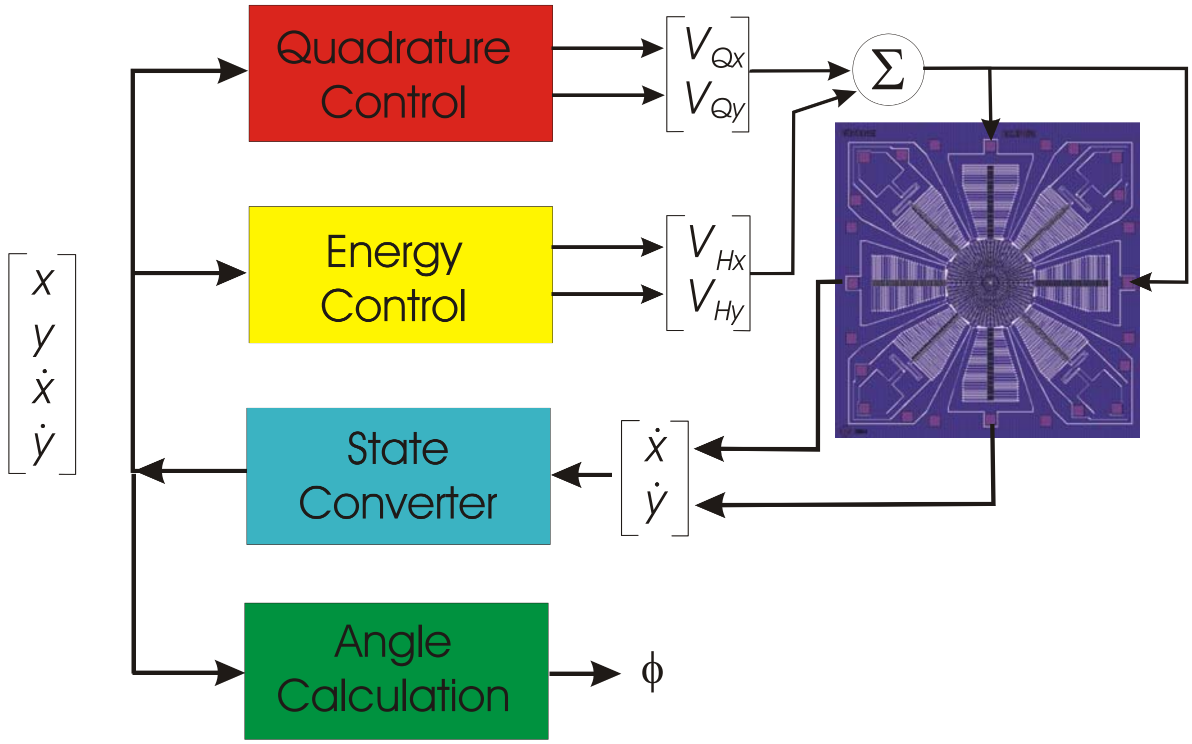

Figure 7: Overview of RIG Control System

Table 3: Control System Parameters

x	Transduced position
y	Transduced position
$\dot{x}$	Transduced velocity
$\dot{y}$	Transduced velocity
V_{Hx}	Energy Correction Voltage
V_{Hy}	Energy correction voltage
V_{Qx}	Quadrature correction voltage
V_{Qy}	Quadrature correction voltage
ϕ	Precession angle

Angle Calculation

Position and velocity information is collected from the sensing systems and calculations are then performed as per

$$\phi = \frac{1}{2}\tan^{-1}\left[\frac{2(\omega^2 xy + \dot{x}\dot{y})}{\omega^2(x^2 - y^2) + (\dot{x}^2 - \dot{y}^2)}\right]. \quad \textbf{Eq. 5.}$$

Energy Balance Control

The energy balance control maintains a constant system energy by compensating for the particular damping effects as separate from Coriolis response. The system energy is determined completely by equations can be shown to be

$$E = \frac{1}{2}\left(\omega^2 x^2 + \omega^2 y^2 + \dot{x}^2 + \dot{y}^2\right) \quad \textbf{Eq. 6}$$

and

$$H = x\dot{y} - y\dot{x} \quad \textbf{Eq. 7}$$

This component compensates for all energy losses to the mass trajectory due to electrical phenomena, fluid damping, and mechanical losses in the suspension system separate from quadrature.

Quadrature Control

The Quadrature control compensates for errors due to the inevitable manufacturing defects that effect suspension components. Special care will have to be taken in the design of the driving portion of the controls in order to minimize the effects on the precession angle.

F. Plan of Research

The following schedule addresses the major technical milestones encountered in the RIG development with some accompanying discussion.

Task 1: MEMS sensor design

The MEMS device will be designed according to a set of rules that are based on the frequency content of the desired rotation rates to be resolved. Briefly, the drive frequency must be of sufficiently high frequency as to make the resolution of rotation possible with in the dynamic system.

Table 4: Target Bandwidth

Rotational Frequencies	System Drive Frequency (carrier)
<200Hz	5kHz – 15kHz

Task 2: Fabrication

Once a design has been validated for the desired attributes the device will be fabricated by way of a deep reactive ion etching (DRIE) process with due consideration to proper aspect compensation to ensure accurate geometry.

Task 3: Packaging

Candidate devices will be mounted within an IC chip carrier (Figure 8) selected for use in the prototyping phase. The packaging at this point serves to facilitate mounting to a prototyping circuit board only.

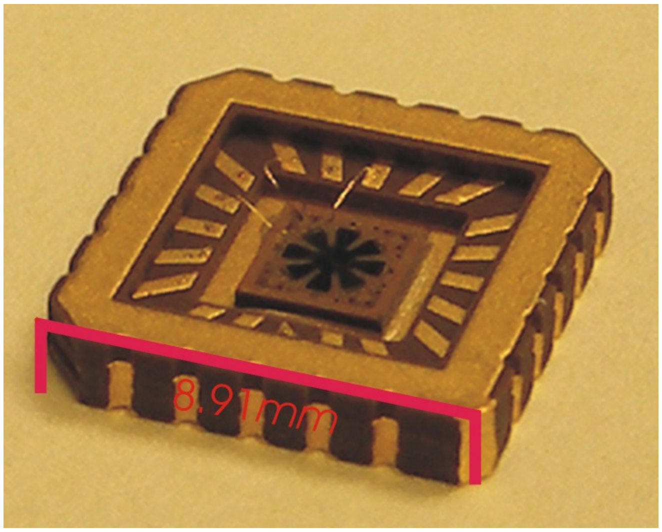

Figure 8: Chip Carrier for Prototyping of MEMS Devices

Task 4. Prototype Amplification and Sensing Interface: Overview

In this scenario (Figure 9) the voltage level proportional to the Coriolis response is sensed differentially. The signals from the sense combs are connected to the transimpedance differential amplifier. This output is then sent to the first lock-in amplifier which demodulates the signal at the carrier frequency. The output then continues to the second lock-in amplifier that demodulates it further at the drive frequency. The result is a DC signal proportional to the rate of rotation of the device. This is the first step in the laboratory characterization. Once this base system has been established control system trials will begin making use of digitally sampled values from the analog domain in the effort to realize the precession angle sensor.

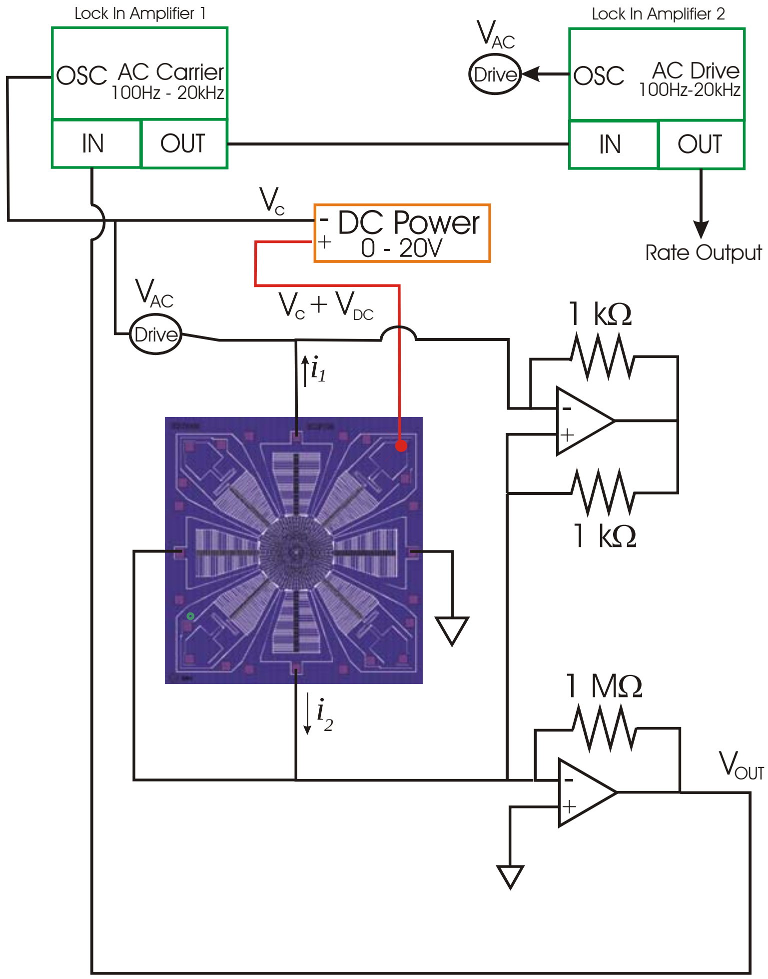

Figure 9: Laboratory Prototyping

Task 5. ASIC Development

ASIC development will involve the design of control and other peripheral electronics needed for driving, sensing and signal processing. Functionality that will be present includes:

- Multiple tunable frequency generators
- Charge pump voltage supply
- Demodulation circuitry
- Transimpedance amplifiers
- Integrators
- Common-mode rejection circuits, unit gain differential amplifier, or other noise reduction systems

Task 6: RIG Control System Development and Integration.

The control system will be developed with the use of MEMS prototypes. Tuning of the control system parameters is vital for successful operation of the sensor. At this stage the control system is comprised of a bench-top prototype where the processing occurs in the digital domain by way of a PC-based data acquisition system.

Task 7: RIG Characterization of Deterministic Errors

The following characteristics will be determined using methods developed at MEMSense.

1. Scale factor cross sensitivity
2. Scale factor acceleration dependence
3. Bias temperature dependence

Task 8: Proof of Concept, Bandwidth characterization, and Control System Tuning.

Bandwidth depends heavily on the rate at which energy can be added to the system without dissipation due to stress and other mechanical losses. Some electrodynamic effects will factor in as well.

In general, the gyroscope is a spring-mass-damper system of the form:

$$\ddot{x} + \delta\dot{x} + \omega^2 x - 2\Omega\dot{y} = 0 \qquad \textbf{Eq. 13}$$

$$\ddot{y} + \delta\dot{y} + \omega^2 y + 2\Omega\dot{x} = 0 \qquad \textbf{Eq. 14}$$

This system is considered for discussion of the order of magnitude of the various terms involved in the system while also noting that there will be multiple additional terms both mechanical and electrical that also figure in but are assumed to be quite small. A particular system can be characterized by the Q factor which is indirectly proportional to the damping coefficient.

Various grades of inertial measurement are separated in to a few categories and bandwidth often follows:

Table 5: Gyroscope Bandwidth Performance
adapted from [4]

	Rate Grade	Tactical Grade	Inertial Grade
BW (*Hz*)	<70	$\approx$ 100	$\approx$ 100

Table 6: Performance Requirements for Various Inertial Applications
adapted from [5]

Application	Bandwidth	Resolution	Dynamic Range
Auto Rollover	0-100Hz	<1°/s	±100°/s
Active Control Systems	0-100Hz	<0.1°/s	±100°/s
Inertial Grade	0-10Hz	$<10^{-4}$ °/s	±10°/s
Platform Stabilization	0-100Hz	<0.1°/s	±100
Headmounted Display Data collecting gloves	DC – 10Hz	<0.1°/s	±100°/s
Pointing Devices for Computer Control	DC – 10Hz	<0.1°/s	±100°/s
Robotics	DC – 100Hz	<0.01°/s	±10°/s

D. MEMSense Personnel

James P. Brunsch Jr.

Chief Technical Officer
MEMSense, LLC
2693D Commerce Rd.
Rapid City, SD 57702-8071

Professional Preparation
Southern Illinois University at Carbondale, Electrical Engineering B.S.E.E.T., 1996

Appointments

MEMSense, Rapid City, SD October 2001-Present
Principal Owner, Chief Technical Officer/ Electronics Engineer
Oversee all aspects of company operations including financial, business development, human resources, technical product development and direction, equipment acquisition, customer and investor relations. Direct company research and development while participating in inertial system, electronics and MEMS sensor design. Technically assist customers in system developments for application specific inertial sensors and systems.

Comuniq, Inc., Rapid City, SD March 2000 – October 2001

Vice President of Sales

Defined sales processes for entering market with a complete VoIP solution. Researched VoIP competition's pricing, technical features, quality, and company stability. Researched existing communications technologies and architectures employed in the Public Switched Telephone Network (PSTN). Researched and evaluated emerging communication technology platforms for products possibly strengthening our VoIP market entry. Developed and initiated many contract agreements with various equipment and service providers.

Hardware Group Management

Managed group of hardware design engineers, consultants and interns. Composed new product development strategy. Created new product specifications and architectures. Performed and coordinated design reviews. Created design documentation system. Directly performed digital electronics and PCB design. Managed overseas manufacture of product line.

Digirad Corp., San Diego, CA October 1996 - March 2000

Electronics Engineer, Camera Development

As electronics engineer in camera development performed various electronics subsystem design duties from concept prototypes to full production units. Further activities involved supporting senior research scientists in gamma camera detector development with the design of extremely low noise experimental electronics systems and assisting in experiments.

Collaborators: *Professionals:* Robert Dean, George Flowers, and Scotte Hodel, Auburn University; Thomas Hancock and Audi Scott Boeing Company; Jeff Blankenship and Eric Pierce, NSWC Panama City; Jonathan Jones and Brian Medley, NTA, Inc.; Chris Abdnour, U.S. Special Operations Command. Julian Cothran, David Bittle, Rob Glover, Brian Grantham, Gary Jimmerson, Ken Pruitt, Patrick Renfroe, and Mike Turner, U.S. Army;

Samuel B. French

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Education

South Dakota School of Mines and Technology, Department of Physics M.S. 2002

South Dakota School of Mines and Technology, Department of Physics B.S. 1999

Experience

Research and Development, MEMSense, LLC.

Research Scientist –Activities at MEMSense have included the design of MEMS sensors and characterization of noise in novel MEMS gyroscopes. He has characterized systematic and random noise in MEMS devices in various levels of integration with inertial measurement systems including development of methods for compensation of systematic noise components in MEMS inertial sensors.

- Test design for severe shock environments.
- MEMS Gyroscope design and characterization
- Control system design for MEMS inertial sensors.
- Investigation of innovative MEMS packaging techniques.

Research Assitant **Dept. of Physics, South Dakota School of Mines and Technology**
Advisor: Dr. Michael G. Foygel
Computer modeling of 2-D and 3-D composite materials (carbon nanotube suspensions). Analyzed critical phenomena related to conductivity; applied percolation theory extensively in this work. Worked with a theoretical team as well as individually throughout this research. Determined the dependence of aspect ratio on the critical concentration of nanotubes in infinitely large disordered systems. 2001 – 2003.

Publications

1. THEORETICAL AND COMPUTATIONAL STUDIES OF CARBON NANOTUBE COMPOSITES AND SUSPENSIONS. Phys. Rev. B **71**, 104201 (2005). With A. D. Morris, D. Anez, M. Foygel, and V. L. Sobolev.

2. MONTE CARLO SIMULATION OF NANOTUBE SUSPENSIONS AND COMPOSITES. Technical Proceedings of the 2003 Nanotechnology Conference and Trade Show, vol. 3, pp. 149-151 (February 23-27, 2003, San Francisco, CA, U.S.A.) With R. D. Morris, D. Anez, M. Foygel, and V. Sobolev.

Collaborators

Robert Dean, Foster Dai – Auburn University

Keith Benson

Software Engineer
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Education

South Dakota State University 1993 B.S. Electronic Engineering Technology

Experience

MEMSense Inc, Rapid City, SD **February 2003-Present**

Software Engineer

Developed a 3-D graphics program for analysis of real-time data. Developed a 2-D graphics biofeedback program designed for use with a heads up display. Converted the communications mechanism of a client-server application from named pipes to TCP/IP.

Design and develop firmware for embedded processors including the 8051 and TI DSPs. Develop algorithms for correcting inertial measurement systems.

ConvergedNets Inc., Rapid City, SD **June 2002 – December 2002**

Software Engineer

Researched Open-Source Voice over IP solutions. Investigated feasibility of using Linux in a production environment

Comuniq, Inc., Rapid City, SD **March 2000 – June 2002**

Software Engineer

Assisted with porting a C++ telephony product from the Windows NT platform to Linux. Issues included multi-threading and synchronization. Performed bug-fixes and enhancements on a VoIP Gateway. Developed group level regression tests. Automated several aspects of the development process.

Raytheon ITSS, EROS Data Center, Sioux Falls, SD **May 1998 - March 2000**

Software Engineer

Member of team responsible for maintenance of the Image Analysis System (IAS). The IAS supports the characterization and calibration of Landsat 7 data. The IAS consists of C, IDL, SQL, and PL/SQL code along with an Oracle database. Provided support for operations. Wrote detailed designs for both bug fixes and upgrades to the current system. Implemented changes in C, IDL, and SQL. Analyzed problem reports submitted by users. Performed regression and system tests. Wrote PERL and shell scripts to automate common tasks such a building software and regression testing.

USGS, EROS Data Center, Sioux Falls, SD **January 1996 - March 2000**

Physical Science Technician

Developed programs in C, C++ and IDL. Maintained existing programs. Assisted in the development of algorithms for the radiometric calibration of Landsat 5 and Landsat 7 data.

E. Facilities

MEMSense Facilities

MEMSense manufactures and develops the world's smallest inertial measurement units and triaxial inertial sensors. The MEMSense staff has significant experience in the applications of MEMS inertial sensors. The facilities present at MEMSense are ideal for dynamic characterization of inertial sensor technology in a variety of environmental conditions.

Equipment in the MEMSense laboratories and manufacturing facility:

1. Multiple precision angular rate tables with thermal environment capability from -60 C to +150C by way of dedicated liquid nitrogen injection systems combined with oven testing chambers. Testing processes can be fully automated with sophisticated data collection and analysis.
2. Centrifuge table with 100g capability also enclosed within a testing chamber with environment capability from -60 C to +150C.
3. Impact test station with capabilities to 4000 g with a variety of test waveforms available. This may be used to evaluate the performance of advanced MEMS RIG configurations utilizing vibration rejection methods.
4. Electrodynamic Shaker Vibration system capable of sine and random testing with frequency content from 1Hz – 4kHz.
5. Automated manufacturing facility.

Design, Prototyping and Manufacturing

MEMSense has provided prototyping and manufacturing of MEMS based inertial measurement solutions for over five years. The experienced engineers at MEMSense have devised solutions to demanding customer specifications and have therefore been on the forefront of the effort to introduce MEMS inertial sensors into numerous and novel applications.

Auburn Facilities

Auburn University has extensive MEMS, electronics and packaging capabilities, from design to implementation. Within the Department of Electrical Engineering, there is approximately 8500 square feet of laboratory space set aside for microsystems development and testing, including integrated circuit and MEMS device fabrication, thick film hybrids fabrication, die and component level packaging, circuit board assembly, environmental testing and failure analysis. Additional capabilities include extensive CAD and other software tools for microsystem design, simulation and development, including Cadence, Mentor Graphics, IntelliSuite, Coventorware, OrCAD, Zemax, Lavenir, Lasi, and AutoCAD. Auburn University's microsystems capabilities cover not only the micro-device design and fabrication, but also the design and implementation of the support electronics and software necessary for integrating micro-devices and microsystems into useful end applications.

- Microfabrication capabilities:
- STS, ASE, DRIE and AOE deep oxide etch,
- oxidation/diffusion furnace,
- LPCVD,
- aligned frontside/backside photolithography (Karl Suss MA/BA 6 mask aligner),
- anodic bonding, polyimide curing,
- wet processing (including HF release),
- CPD, plating, a CHA Mark 50 7-E-beam target + 1 sputter target vapor deposition system with dual E-gun capability for co-deposition, and inspection.

G. References

[1] Friedland, B., and Hutton, M. *Theory and Error Analysis of Vibrating Member Gyroscope*, IEEE Transactions on Automatic Control, Vol. AC-23, No. 4, August, 1978.

[2] Clark, William A., *Micromachined Vibratory Rate Gyroscopes*, PhD. dissertation, Dept. of Electrical Engineering and Computer Science, University of California, Berkeley, 1997.

[3] Painter, C., *Micromachined Vibratory Gyroscopes with Imperfections*, Ph.D. dissertation, Dept. of Mechanical and Aerospace Engineering, University of California, Irvine, 2005.

[4] N. Yazdi, F. Ayazi, and K. Najafi. *Micromachined Inertial Sensors*, Invited Paper, Proceedings of the IEEE, 86(8):1640–1659, August 1998.

[5] Beeby, S, et al., *MEMS Mechanical Sensors*, p. 174, Artech House, Inc., Boston, 2004.