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Integrated Microgyroscope

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ABSTRACT

SatCon Technology Corporation is developing a prototype electrostatically suspended micromechanical gyroscope in the Small Business Innovation Research (SBIR) program under Contracts 19282, and 19585 from NASA Langley Research Center. This paper presents the results of the Phase I feasibility study and the plans for fabrication in the upcoming Phase II program.

1. INTRODUCTION

SatCon Technology has performed a study of micromechanical gyroscopes. The goals of the Phase I SBIR program were to define a baseline system configuration and establish technical feasibility. In the Phase II program, just beginning, a prototype actuator will be fabricated and tested. This paper presents a micromechanical device overview, a summary of the Phase I results and plans for Phase II.

2. SPECIFICATIONS AND CONFIGURATION

As with all sensors, resolution, accuracy, large dynamic range, low power consumption, small size and high bandwidth are desired. For this technology effort, the obvious primary objective was small size with the goal of eventually developing a complete two-axis rate gyro on a microchip. For this feasibility study, maximum/minimum angular rates of 10 radians/sec and 0.1 radians/sec and 200 Hz bandwidth were chosen as specification goals to approximate what might be required for use on robotic arms. Other performance specifications were determined by process controlled geometries and parameters as discussed in Section 4.

2.1 Suspended gyro configuration

The initial micro-gyro configuration identified is shown in Figure 1. Configured as a rebalance gyro, this microfabricated machine consists of three types of electroquasistatic components - the motor drive, position sensors, and the non-rotary actuators for rebalance and suspension. Like suspended macroscopic gyros, the rotor is spun by a motor to produce angular momentum, suspended and controlled by force and torque actuators, and sensed by various position sensors. As discussed in Section 2, all the sub-components are electric field devices. The term "rebalance" identifies the gyro mode of operation. When acted on by external forces, the control system is designed to hold the gyro in a constant position, rebalancing it. Knowledge of the actuator control signals and dynamics allows the inputs to be determined. Since the controlled mass (the gyro rotor in this case) is held to a nearly constant position, the linearity of the sensors and actuators is improved, and the overall dynamics are simplified. A system block diagram is shown in Figure 2.

The electrostatic force can be written in linearized form for a fixed potential as:

$$F=\frac{1}{2}V^2\frac{\partial^2 C}{\partial^2 X}\Delta X$$

where ΔX represents the excursion about the equilibrium position, and the coefficient is positive. Since the force increases with decreasing distance, the motion is unstable and without other compensation requires closed loop control. In the case of a fully suspended rotor, this control must be effected in both axial and radial directions (five unstable degrees of freedom). There are, therefore, four sets of actuator/sensors - two for the upper and lower axial suspension and two for upper and lower radial rebalance actuator/sensors - and the motor driver actuator; hence the multilayered configuration of the figure.

The fabrication of such a multi-actuated, multi-sensed device requires at least five sets of alternating insulating/conducting layers on the rotor. For reasonable capacitive bias currents and actuator forces, the facing areas must be at least 1-2 μm high with radial gaps of the same order. The height of this rotor will accumulate to over 5μm. Present technology, however, only makes feasible aspect ratios (rotor thickness to gap) of up to 2/1, with 1/1 being typical. This gap in fabrication technology will have to be bridged to allow successful fabrication of a fully suspended micro-gyro.

2.2 Motor configuration

The electrostatic production of torque has long been considered for motor drives. Four classes of electroquasistatic motor actuators have emerged which have analogues with magnetically operated devices - variable capacitance, electrostatic induction, permanent electret, and electric hysteresis. In the work by Bart, induction and variable capacitance motors were studied in detail with attempts made to fabricate both axial gap and radial gap variable capacitance motors. Radial gap variable capacitance motors have been successfully built and tested at both MIT and Berkeley. Our system therefore baselined a radial gap motor as fabricated at MIT[2].

2.3 Sensor configuration

The baseline sensor configuration chosen was capacitive position sensing using a superposition of high frequency signals between the axial control electrodes and the rotor. Decomposition of the four sensor signals (one for each axial stator electrode) provides the signals needed to control the rotor. Capacitive position sensing is commonly used in macroscopic devices, and has also been successfully applied to other micromechanical devices. The basic concept is to drive a constant current across an air gap (whose capacitance varies inversely with gap distance) and read the resulting voltage which is linearly proportional to the gap. High frequency modulation and demodulation allow good noise immunity. Though the capacitance of the microgyro axial gap will be very small (about 3×10^{-14} farads), the placement of FETs (field effect transistors) on the silicon substrate as preamplifiers as done by Schmidt should allow reasonable measurements to be made[3].

3. ELECTROMECHANICAL DESIGN

The design of the motor drive and rebalance actuator is based on the specifications discussed in Section 3, many of which were derived from known fabrication constraints and experience. Dimensions were generally conservatively chosen given the uncertainty in fabricating devices with this technology. In practice, some or all of these dimensions may be changed in the prototype development effort. These sizing numbers, however, represent what would be required for engineering development of a useful instrumentation sensor.

3.1 Sizing

The overall rotor diameter, 200 μ, was chosen as the largest size that could be fabricated without significant warpage due to residual stress buildup during fabrication. The rotation rate is constrained by stress limits in the rotor and electronics limits in the motor driver circuitry. A rate of 500,000 rpm (8.3 kHz) was chosen as a reasonable extension of current motor rates (about 50,000 rpm). This is well below the ultimate spin rate (about 10,000,000 rpm) determined by material strength limits and is limited by motor drive electronics. The required electronics frequency, 25 kHz, is attainable without excessive noise problems. The motor height was set to 2.2 μ, the same height as currently fabricated micromotors. The maximum value of total rotor thickness is limited by fabrication technology to about 2 times the radial gap of 1.5 μ. The axial gap between substrate and rotor was set at 2 μ. This represents a tradeoff between gap capacitance and rotor unstable frequency. A smaller gap would make sensor measurements more accurate at the cost of raising the unstable frequency and complicating the control problem. The 2 μ gap gives a 300 Hz unstable frequency.

3.2 Sensor/Actuator

The four segment rebalance sensor/actuator electrode design is similarly derived from the specifications. While it was not attempted to optimize the pattern for torque, depositing the conducting region from 0.7 R to 1 R gives adequate rebalance torques and adequate capacitance for sensing inclinations as small as 0.008°. A possible difficulty is the actually attainable depth and uniformity of the implanted electrodes since the thermal noise limit is sensitive to circuit resistance. The sensor capacitance between each of the four electrodes and the rotor is approximately 3×10^{-14} F. With a typical commercial oscillator frequency of 100 kHz, the sensor current is about 15 nA for operation at 0.8v. Since commercial devices sense capacitance in the same range (although with larger electrode and gaps) it should be possible to use standard techniques for angle information.

3.4 Summary

The tables below give a summary of the dimensions and parameters predicted for the two degree of freedom microgyro with specifications as discussed in Section 2.

Spin Angular Speed	500 kRPM
Spin Moment of Inertia	1.5x10-18 kgm-m2
Precession Moment of Inertia	8x10-19 kgm-m2
Minimum Angular Rate	0.01°/s
Thermal Sensor Noise	< 0.4x10-3 v
Angular Sensitivity	< 0.008°
Sensor Electrode Capacitance	3x10-14 F
Sensor Operating Current (0.8 V)	15 x10-9 A
Nominal Drive Actuator Potential	0.5 v
Drive Torque Per Pole	10-11 N-m
Rotor Radius	50μm
Radial Gap	1.5 μm
Vertical Gap	2 μm
Rotor Thickness	2.2 μm
# Stator Poles	12
# Rotor Poles	8

4. CONTROL AND ELECTRONICS DESIGN

4.1 Control System

This section presents the controller design philosophy. For a more detailed description of the controller, the reader may refer to Reference 4. As shown in Figure 2 the system block diagram consists of the actuator and plant (gyroscopic) dynamics, the sensors, the controller, and the decomposition electronics. One of the goals of the controller is to keep the orientation of the rotor fixed, in the null position, relative to the orientation of the "stator" frame of the gyroscope. In addition, the controller must provide accurate measurement of the torque that is required to maintain the rotor in the null relative orientation. As usual, the simplest controller that can meet the performance objectives is desired in order to minimize hardware complexity. In particular, a fixed-gain, linear controller is desired that can be easily implemented in analog electronics. This will force some performance and stability robustness tradeoffs, in particular because the plant dynamics are a strong function of the operating speed and are open-loop unstable. Because of the open-loop unstable nature of the plant -- an inverted pendulum at low speeds -- closed-loop control is required from zero speed to the full operational speed. The challenge, then, is to find a fixed gain controller that will provide adequate performance at all speeds.

The design approach to develop a fixed-gain controller for this speed varying plant was to first examine how optimal, full-state feedback controllers change with changing plant speed. These full-state feedback controllers assume knowledge of the position and velocity of the rotor in both radial directions. Based on the behavior of these parameter-varying, full-state feedback controllers and the addition of some physical insight, a fixed-gain, full-state feedback controller can be chosen that provides reasonable performance over the full speed range. This full-state feedback controller is then implemented as an output feedback controller using lead-lag compensators to provide estimates of the velocity.

4.2 Electronics

4.2.1 Sensor electronics

The capacitance of the position sensor varies inversely with the distance from the sensor to the target. Over the specified measurement range, the sensor varies in capacitance from approximately 0.027 picofarads (pF) to 0.033 pF. Any stray capacitance on the sensor leads will effect the linearity of the measurement unless the leads are appropriately guarded. The ability to detect position accurately is also hampered by any load placed on the sensor capacitance by the measurement electronics.

A block diagram of the sensor electronics is shown in Figure 3. The sensor is driven by a 100 kHz current source so that the resultant voltage is proportional to the sensor impedance. The AC voltage produced across the sensor is buffered by a "guard" loop, full-wave rectified, and low-pass filtered to produce a DC output voltage directly proportional to distance. The effects of stray capacitance on the sensor leads are greatly reduced by driving the shield of the sensor cable with a "guard" loop. The guard loop drives the shield with a voltage identical to that across the sensor, and thus no current flow is possible. The impedance of the shield is a capacitance greater than 200 pF to ground. In order to drive this load, the voltage across the sensor is buffered by the FET input stage, a high-bandwidth differential op-amp, and a high-current buffer. The bandwidth of this follow-up loop must be high to reduce any effects of the guard capacitance upon the sensor capacitance. To reduce the input capacitance of the sensor electronics, a Field Effect Transistor (FET) input stage is used. This input stage presents a very high resistance and low capacitance load to the sensor. The FET input stage is configured as a source-follower where the source signal will exactly follow the gate (input) signal. The source terminals of the FETs are each loaded with a transistor current source. The high impedance of the current sources reduces the effect of any gate-to-source capacitance. The drain of the FETs are capacitively coupled to the buffered sensor voltage to reduce the effects of any gate-to-drain capacitance. Stray capacitance on the circuit board would be reduced by placing the buffer-loop circuitry on a copper-clad board with the copper clad driven by the guard voltage. The output of the sensor guard-loop is bandpass filtered to eliminate both DC drift and high-frequency noise effects. The signal is then full-wave rectified and low-pass filtered to produce a DC output voltage.

4.2.3 Motor drive electronics

The gyro wheel-motor is a three-phase bipolar variable-capacitance motor. Since this motor type is synchronous, i.e., produces torque only when the rotation frequency and excitation frequency are the same, it requires a variable-frequency drive source. In addition, the push-pull excitation required for each of the three bipolar phases will require six high-voltage output stages.The motor is driven with balanced bipolar voltages so that the rotor will remain near ground potential. Any voltage induced on the rotor will cause it to be strongly attracted to the grounded substrate because of its large surface area.

Motor start-up will require that the excitation frequency start at the sub-Hertz level and ramp up to the full-speed value of 25 kHz. This will be accomplished with a ramp generator and voltage-to-frequency (V/F) converter. The bipolar three-phase generator takes the single-phase output of the V/F converter and produces three square-waves with 120 degrees phase difference and their complementary signal for driving the output stages. In addition, the circuit generates the signal pair which develops the bipolar waveforms. The output circuit contains six high-voltage drivers and can deliver up to 120V.

5. FABRICATION

Fabrication is a major challenge with micromechanical systems. Overall system feasibility and functionality are more closely tied to fabrication methods than with macro scale systems. For this program, it is planned to use the microsystems fabrication facilities at MIT and base the motor design on those developed there. The program will be broken into three technology demonstration steps aimed at verifying component technologies before integration into a complete system.

The first step will be the fabrication of a capacitive sensor demonstration unit. This will consist of a microfabricated cantilever beam and a differential field effect transistor pair. The FETs will be connected to an electrode below the cantilever and serve as the capacitive sensor pre-amplifier as discussed in Section 5. Optical methods will be used to independantly verify the position of the cantilever.

The next technology demonstration will be a non-rotating closed loop suspension of microfabricated plate. These prototypes will be used to develop specific mechanical, electrical and control designs and fabricaion sequences for the integration of sensor technology into a micro-suspension system. Testing will verify actuator and control characteristics and allow the development of a rotating micro-suspension

Finally, after the first two tasks, the rotating, suspended microgyro will be developed. This will extended the non-rotating suspension with a motor drive and additional electronics. It is anticipated that substantial process development may be necessary for the successful completion of this task.

6. CONCLUSIONS

The results of the feasibility study were very positive. Though extensions of fabrication technology will be required for fabrication of the prototype device, the potential for successful development is very good. An operational micromechanical gyroscope would have many applications in commercial, aerospace, and military sectors.

7. REFERENCES

1. Howe, et all, "Silicon Micromechanics: Sensors and Actuators On A Chip", IEEE Spectrum , July 1990.

2. Bart, S.F., Modeling and Design of Electroquasistatic Microactuators, Ph.D. Thesis, MIT, September 1990.

3. M. Schmidt, et all, "Surface Micromachining of Polyimide/Metal Composites For a Shear Stress Sensor", in IEEE Micro Robots and Teleoperators Workshop, Hyannis MA 1987.

4. Hawkey, T, and Torti, R. "An Integrated Microgyroscope", Final Report, contract NAS!-19282, SatCon Technology Corporation, Cambridge, MA July 1991.

8. FIGURES

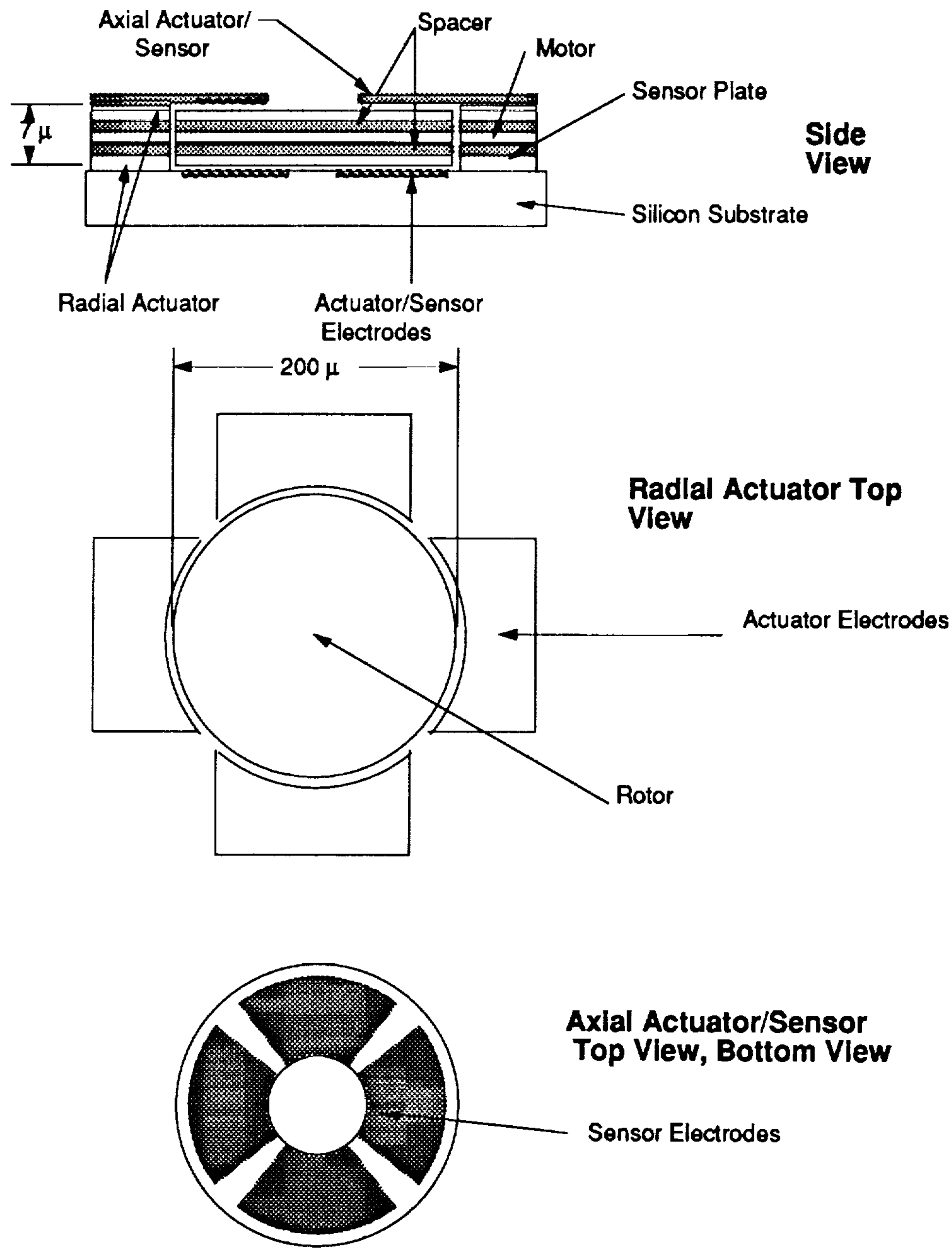

Figure 1. Suspended Microgyroscope Configuration

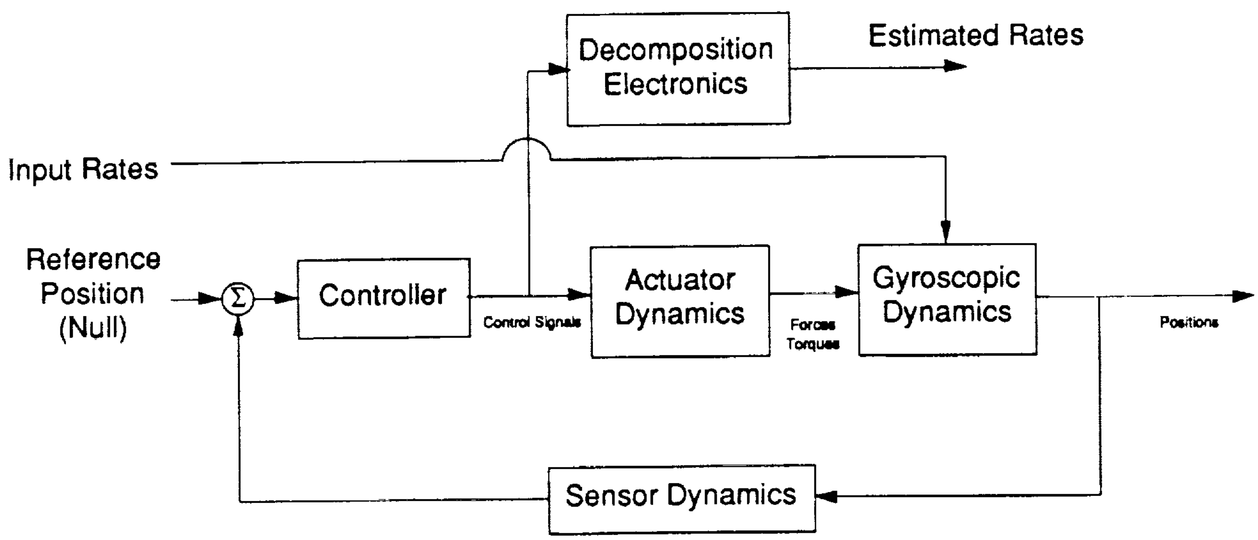

Figure 2. Microgyro Block Diagram

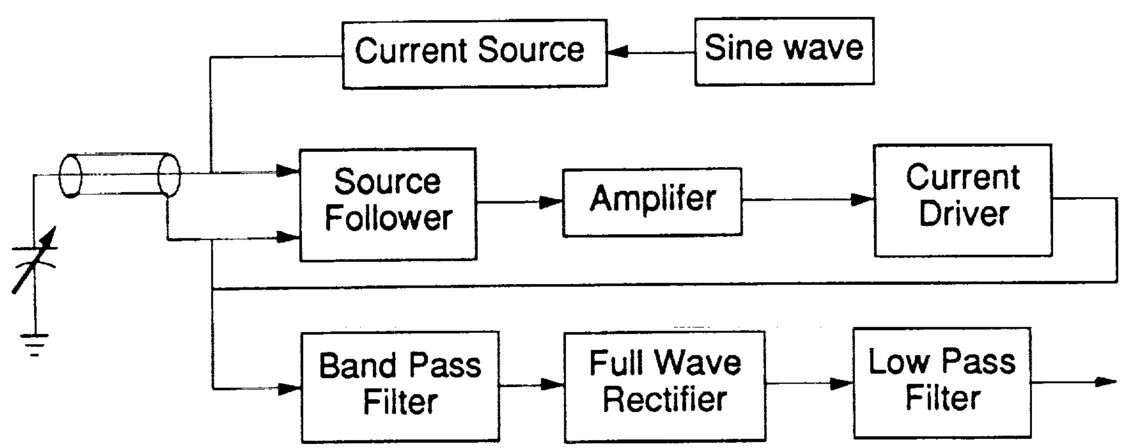

Figure 3. Sensor Electronics Block Diagram