*Presented at Biomedical Engineering Society Annual Meeting (BMES), Phoenix, AZ, USA, Oct 11-14, 2017*

# Performance Requirements of MEMS based Vestibular Prosthesis

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**Introduction:** Hearing, vision, and balance are supported by the vestibular system. Dysfunction of the vestibular organs results in losing balance, consequently dizziness, gaze, and images instability. While MEMS-based vestibular prosthesis (VP) have the potential to restore the balance function of patients with instability problem, the analysis of sensor performances and long term drift underlying this rehabilitation is lacking. This paper presents the detailed analysis of sensors performance and derive the requirements for development of vestibular prosthesis.

**Materials and Methods:** The transfer function involved in the vestibular organ of squirrel monkey has been modeled by [1] relating head rotation to neural firing rate. In a VP, the rotational movement is captured by a gyroscope sensor. This sensor suffers from bias (B) and scale factor (SF) drifts (<10% for the rate grade class). Allan variance method is used for noise analysis, and the variation in the delivered pulses are used to demonstrate the effect of sensor drift.

**Results and Discussion:** Vestibular losses significantly increase the detection threshold from 0.5 °/sec to 5.8 °/sec [2]. Under no input rotation, the baseline activity of the electrical stimulation deviates from 125 Hz to 275 Hz under 10% changes in B & SF (Fig.1). As a result of long term drift for the prosthetic device, a normal human sensitivity will fall into vestibular dysfunction (Fig.2), therefore continuous sensor calibration is required.

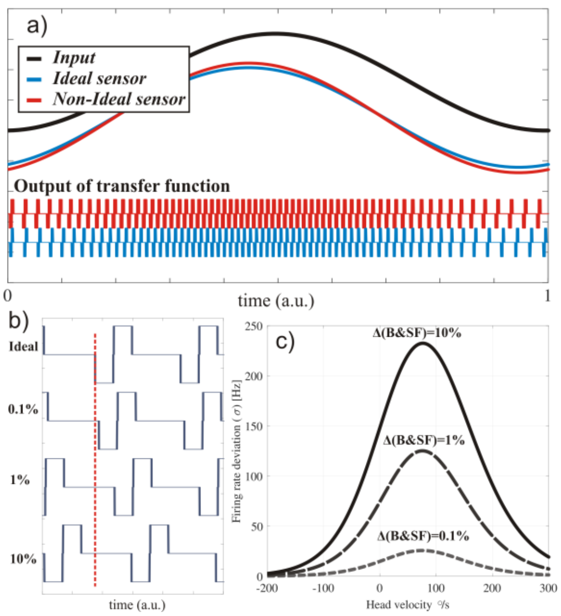


**Figure 1.** Input-output relationship of vestibular transfer function and its simulation result including B & SF drifts on biphasic electrical stimulation pulses to vestibular nerve. a) response of the system in presence of drift, b) biphasic current pulses delayed due to sensor B & SF drift, c) variation of firing rate output pulses vs. head velocity under different drift conditions.

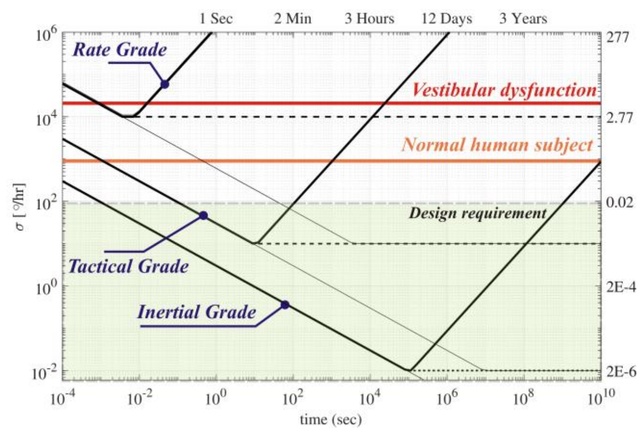


**Figure 2.** Allan variance estimations of sensor output drift and its propagation over time due to Mechanical-Thermal Noise. Simulated noise performance and the trade-off of different rotation sensor grades compared to minimum detectable motion sensation by human subjects.

**Conclusions:** We analyzed the challenges involved in the implementation of vestibular prosthesis based on MEMS vibratory gyroscope. We considered the drift of MEMS sensors and calibration algorithms to reduce sensors drifts under varying dynamic and environmental conditions. We concluded a MEMS gyroscope with a minimum bias instability of 100°/hr would satisfy the design requirements for a VP. These analyses are essential since they determine the ultimate feasibility of the prosthesis.

**Acknowledgements:** This material is based on work supported by Broadcom Foundation.

**References:**

[1] C.C. Della Santina, et al. IEEE Trans Biomed Eng, (2007), 54:1016-30
[2] Y. Valko, et al. J. Neurosci, (2012), 32:13537-42.

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# AUGMENTING MEMS-BASED VESTIBULAR PROSTHESIS WITH SMART AND CONNECTED HEALTH

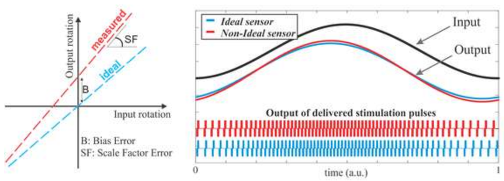
Sina Askari and Andrei M. Shkel
2017 UCI-UCLA Student Research Workshop & Symposium

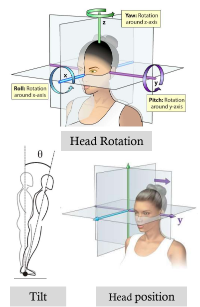
## Objective:

- MEMS devices suffer from Bias and Scale Factor drift during operation.

## Proposed solutions:

- For vestibular prosthesis applications long-term bias and scale factor calibration is needed



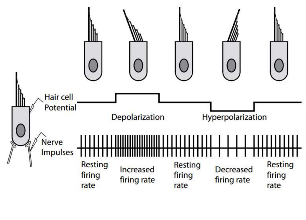
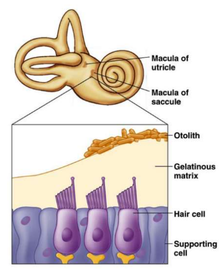
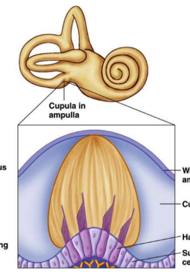




Illustration of Vestibular nerve activity to angular motion and linear acceleration



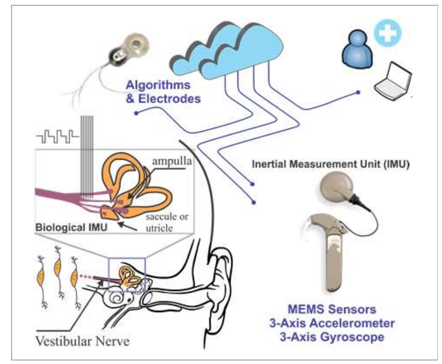

Linear acceleration




Angular motion

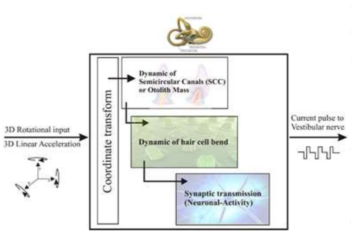
Photos courtesy of Pearson education Inc. publishing as Pearson Benjamin Cummings, Hearing and Balance, University of Wisconsin Madison (hair cell) and Sensation & Perception, 2015 (headshot)

The vestibular system function: body balance, spatial orientation, sustained vision



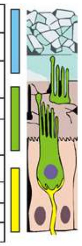

## MEMS-based Vestibular Prosthesis

### Mechanism of the Vestibular Organ

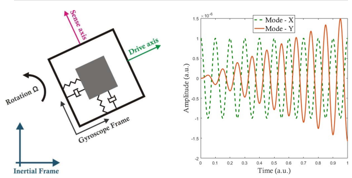



### Model Considerations on all 3 Levels

| Vestibular System Functions | Different Approaches | Mathematical Model | |
|---|---|---|---|
| Coordinate transform | | 3-Semi Circular canal **SCC** (3-axis gyroscope) | 2-otoliths (**Utricle** and **Saccule**) (3-axis accelerometer) |
| Neural Dynamic (ND): -Differential equations | *Goldberg* | $\Theta\frac{d^2\xi}{dt^2}+\Pi\frac{d\xi}{dt}+\Delta\xi(t)=\Theta\alpha(t)$ $H(s)=\frac{\tau_A s}{(1+\tau_A s)}\frac{(1+\tau_L s)}{(1+\tau_1 s)(1+\tau_2 s)}$ | $H_{oto}(s)=\frac{1}{(1+\tau_M s)}\frac{(1+k_A\tau_{A,oto}s)}{(1+\tau_{A,oto}s)}$ |
| | *Milsum* | $\frac{\phi}{\Omega}(s)=\frac{\alpha T_1 T_2 . s}{(T_1 s+1)(T_2 s+1)}$ | |
| | *Soto* | | $\begin{cases} C_2\frac{dV_2}{dt}=I_{syn}-I_{Na}-I_K-I_{L2} \\ \tau_2(V_2)\frac{dn}{dt}=(n_\infty(V_2)-n).a^{\frac{T-T_0}{10}} \end{cases}$ |
| Frequency Modulation (FM): -Look up table | *Santina* | $f=0.5\times f_{max}\times(1+\tanh(A+C(\frac{X_i}{2048}-1)))$ $A=tanh^{-1}(2\times f_{baseline}/f_{max}-1)$ | |
| | *Merfeld* | $f=f_{middle}+f_{range}\left[\tanh(\frac{\omega}{S_{shape}})\right]=150+100\left[\tanh(\frac{\omega}{250})\right]$ | |
| | *Indiveri* | $f=\frac{f_{max}-f_{min}}{2\lvert Limit_c\rvert}Reading_c+\frac{f_{max}+f_{min}}{2}$ | |
| AM (Amplitude Modulation): | *Fornos* | $I_1=gain_{x1}\omega_x+gain_{y1}\omega_y+gain_{z1}\omega_z+baseline\ amplitude$ | |



### MEMS Rate Gyro; Principle of Operation

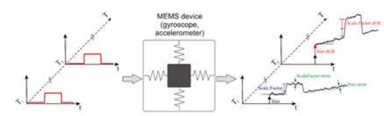



$$m\ddot{x} = -c_x\dot{x}-k_x x+m\left(\Omega^2 x+2\Omega\dot{y}+\dot{\Omega}y\right)+F_x$$

$$m\ddot{y} = -c_x\dot{y}-k_y y+m\left(\Omega^2 y-2\Omega\dot{x}-\dot{\Omega}x\right)+F_y$$

$$y=\frac{2k\boldsymbol{\Omega_z}x}{\omega_y}\frac{Q_y}{\sqrt{1+4Q_y^2(\frac{\Delta\boldsymbol{\omega}}{\omega_y})^2}}$$

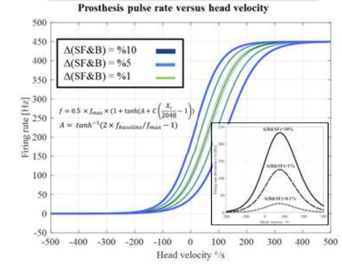
### MEMS Sensor Required Continues Compensation and Calibration




Sources of **ERRORs**:
**Short term** *(high-frequency)*:
Bias & SF error: value changes with time (ARW).
(Corrected by compensation)
**Long term** *(low-frequency)*:
Bias & SF drift: Other influences, environmental, aging and etc.
(Corrected by calibration)

$$\mathrm{ARW_{MTN}} \approx \sqrt{\frac{k_B T\omega_y}{A^2 M\omega_x^2 Q_y}\left[1+\left(\frac{Q_y\left(\omega_y^2-\omega_x^2\right)}{\omega_x\omega_y}\right)^2\right]^{-1}}\ (\frac{rad}{\sqrt{sec}}) \qquad \Omega\propto\frac{1}{A_g A}\sqrt{\frac{k_B T}{M\omega Q}}$$

### Sensor Drift on Neuronal Dynamics

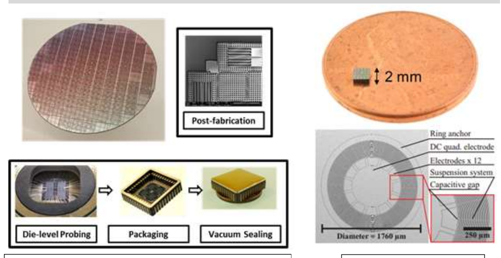



## Approach and Results

### Sensor design

### Algorithm part

### MEMS Fabrication



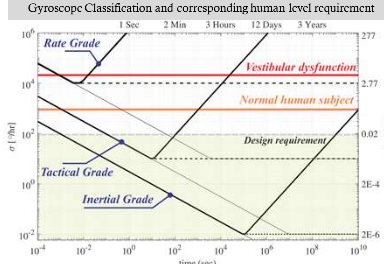

In-house SOI MEMS fabrication and vacuum packaging

Wafer-level encapsulation

S. Askari, M.H. Asadian, K. Kakavand, A.M. Shkel, "Near-Navigation Grade Quad Mass Gyroscope with Q-factor Limited by Thermo-Elastic Damping" Proc. Hilton Head 2016, pp. 254-257

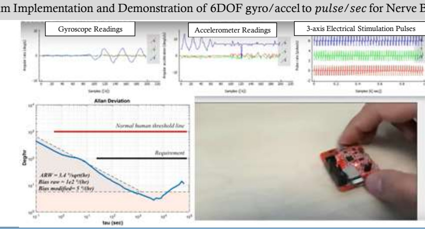
D. Senkal, S. Askari, M.J. Ahamed, E.J. Ng, V. Hong, Y. Yang, C.H. Ahn, T.W. Kenny, A.M. Shkel, "100K Q-factor toroidal ring gyroscope implemented in wafer-level epitaxial silicon encapsulation process", IEEE MEMS 2014

### Gyroscope Classification and corresponding human level requirement




Vestibular loss significantly increase the threshold (~10 fold)

### Algorithm Implementation and Demonstration of 6DOF gyro/accel to *pulse/sec* for Nerve Branches




### Publication

[1] Sina Askari, Mohammad H. Asadian, and Andrei M. Shkel, "Performance Requirements of MEMS based Vestibular Prosthesis," Biomedical engineering society advancing human health and well being (BMES), Phoenix USA, 2017 annual meeting (Submitted)

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