UCIrvine
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MEMS are becoming 3D and atomically precise

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Presentation at **Tohoku University, Japan,** 13 May, 2016

University of California @ Irvine

University of California system

- Founded in 1868, now 10 campuses across California
- 450,000 people total (students, faculty, staff), $23 billion/year

University of California, Irvine

- Founded in 1965, 40,000 people, $2 billion/year
- Ranked #1 of all US universities under 50 years old

UCI Microsystems Laboratory http://mems.eng.uci.edu

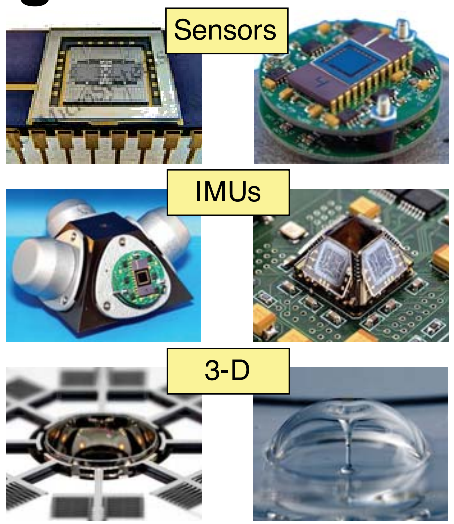
Projects

- Navy gyro and FM IMU
- DARPA PASCAL, MRIG
- Other seedlings etc.

Collaborators

- JPL, ISC8
- NG Navigation Systems
- Foundries: Teledyne, IMT
- Past: NIST, UCB, Systron

- 10 people (8 PhD)
- $2M/year, $2M equipment



MEMS Gyros – Why?

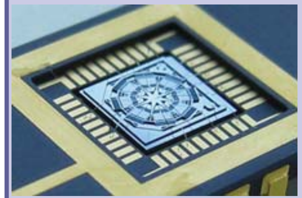
20 years ago
- First silicon MEMS gyro by Draper
- 15,000 deg/h performance

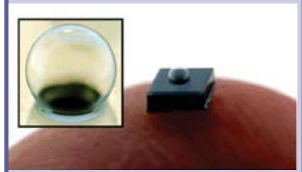
Today
- 10^9 of consumer gyros, 10^6 of automotive
- 10^4 of tactical grade 10 deg/h silicon gyros
- Dozen groups developing 0.1 deg/h gyros

Next 5 years
- Customers will get the first 0.1 deg/h gyro
- Avalanche revolution in market and R&D
- Mid range FOGs, RLGs – out of business
- 10^{12} MEMS IMUs, Internet of Things

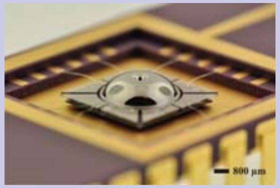
Precision, stability, miniaturization, on-chip multi-sensing functionality

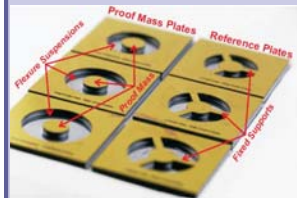
Research Projects


Vibratory Rate Gyros

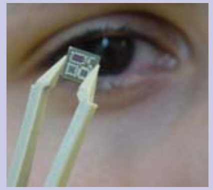

NMR Gyros


MEMS IMU

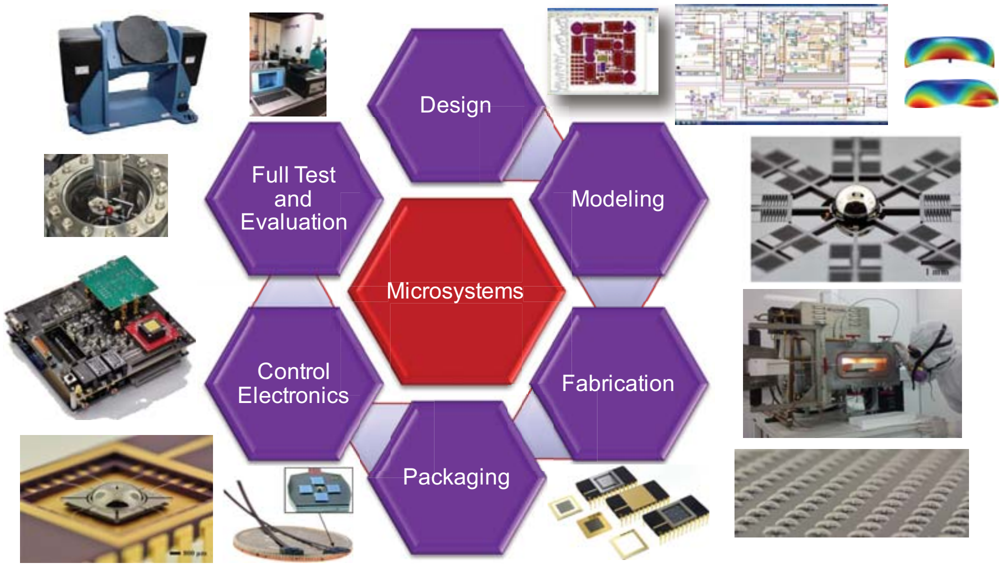

Whole Angle Gyros



Optical Sensors

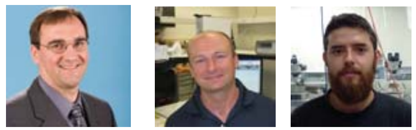

Vestibular Prosthesis

Full Cycle of Development

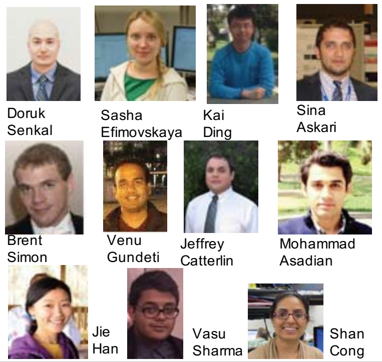


Microsystems Laboratory

Postdoctoral Fellows


Prof. Andrei Shkel, Dr. Sergei Zotov, Dr. Joan Giner

Graduate students


Doruk Senkal, Sasha Efimovskaya, Kai Ding, Sina Askari, Brent Simon, Venu Gundeti, Jeffrey Catterlin, Mohammad Asadian, Jie Han, Vasu Sharma, Shan Cong

Alumni

2013: Igor Prikhodko, Jalal Ahamed, Gunjana Sharma, David Blocher
2012: Elham Asadollahei, Sandeep Kumar, David Markus, Chris Raum
2009: Alex Trusov, Adam Schofield, Monty Rivers, Marc Salleras
2008: Max Perez, E. Jesper Eklund
2007: Jasmina Casals
2006: Ilya Chepurko
2005: Chris Painter
2004: Cenk Acar, Shamaun Holston
2003: Jiayin Liu
2001: Jasmina Casals, Sebnem Eler, Andreu Fargas, Jung-Sik "J" Moon
2000: Johanna Yung

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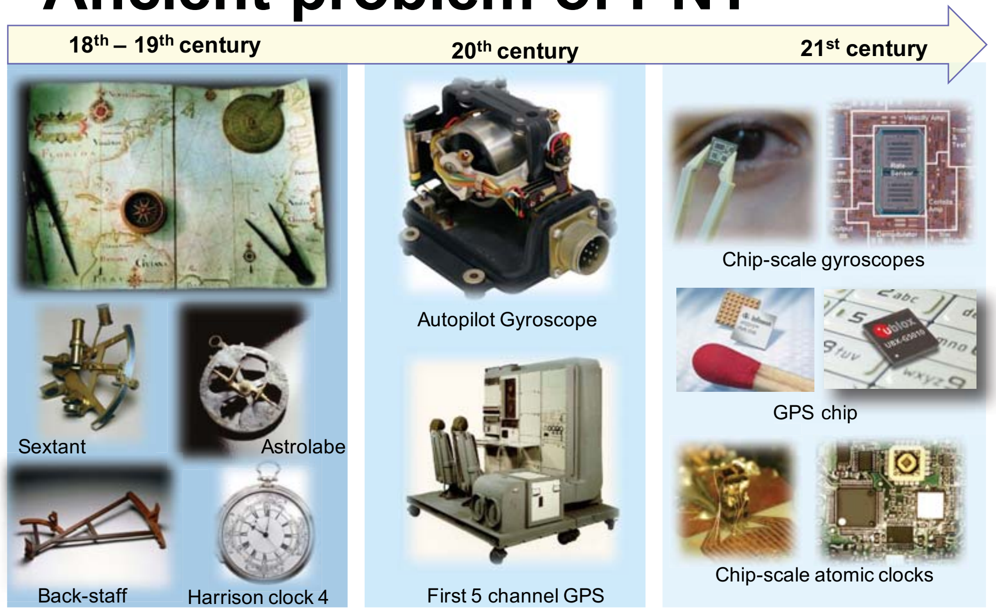
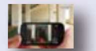
Ancient problem of PNT

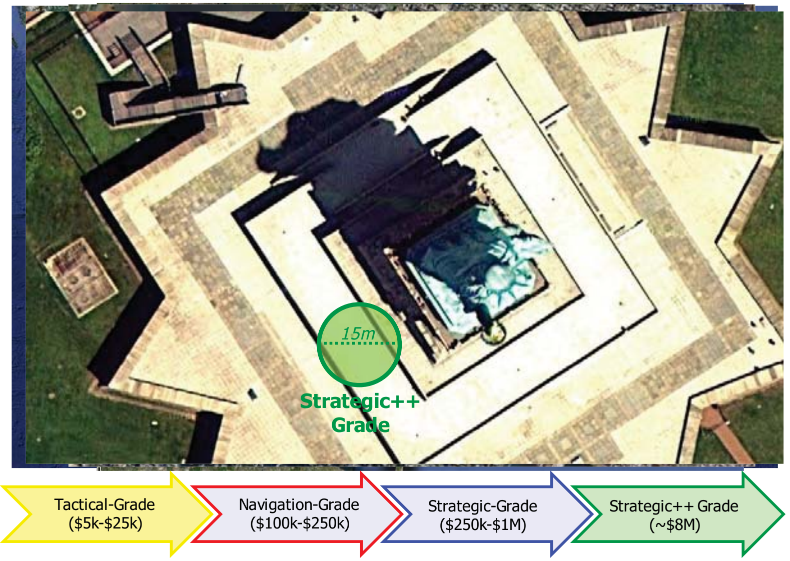


Today's PNT solutions

Solution	Challenge
GPS and GNSS (absolute navigation)  UBX-G5010	▪ 1-10 m CEP: + ▪ C-SWaP of user equipment: +/+ ▪ Availability of signal: +/ - ▪ Resistance to jamming & spoofing: - ▪ Acceptable update rate: +/-
Inertial sensors & Clocks (incremental navigation)  HG1930 MEMS IMU	▪ 10 m CEP in 20 sec (MEMS): +/- ▪ C-SWaP of user equipment: + ▪ Availability of signal: + ▪ Resistance to jamming & spoofing: + ▪ Acceptable update rate: +
Enhanced inertial (e.g., ZUPTing)	▪ > x100 extended operation (app limited)
Radio navigation, Radar navigation	▪ $ engineered infrastructure
Vision-based 	▪ Representation of environment, sensing models, localization algorithms
Signal of Opportunity (SoOP): WLAN (Wi-Fi, Bluetooth, RSS), GSL/3G, AM&FM Radio, DTV, Cellular, RFID	▪ Probabilistic (scenario dependent) ▪ Many challenges: geometry of transmitters, multipath, non-line of sight

Inertial-only navigation

Flight from LA to NYC using inertial-only navigation system



The Grand Challenge

Position Accuracy (CEP):
- Desirable: 10 m after 20 min

$$\text{accel}: 10^{-6}\,[\text{G}] \text{ or } 1\ \mu\text{-G}$$
$$\text{gyro}: 10^{-4}\,[\text{deg/hour}]$$
$$\text{allign}: 10^{-3}\,[\text{rad}] \text{ or } 3.3\ \text{deg}$$

Inertial guidance for munitions

	Time of Flight				
SoA IMU	**10 sec**	**30 sec**	**60 sec**	**3 minutes**	**20 minutes**
0.1 milli-G	0.05m	0.44m	1.77m	15.83m	110.8m
0.02 deg/hr	—	0.004m	0.034m	0.922m	6.454m
1 milli-radian	—	0.002m	0.017m	0.461m	3.227m
RSS	**0.050m**	**0.440m**	**1.770m**	**15.864m**	**111.048m**

	Time of Flight				
SoA Micro-IMU	**10 sec**	**30 sec**	**60 sec**	**3 minutes**	**20 minutes**
4 milli-Gs	1.96m	17.66m	70.63m	633.35m	4,433.45m
4 deg/hr	0.032m	0.856m	6.843m	184.348	1,290.436m
3 milli-radians	—	0.006m	0.051m	1.383m	9.681m
RSS	**1.960m**	**17.681m**	**70.961m**	**659.635m**	**4,617.445m**

	Time of Flight				
MEMS IMU aging	**10 sec**	**30 sec**	**60 sec**	**3 minutes**	**20 minutes**
400 milli-Gs	196.29m	1,766.42m	7,063.22m	63,334.76m	442,343.32m
500 deg/hr	3.961m	106.942m	855.356m	23,043.526m	161,304.68m
3 milli-radians	—	0.006m	0.051m	1.383m	9.681m
RSS	**196.33m**	**1,769.65m**	**7,114.82m**	**67,396.56**	**471,775.92m**

All in presence of

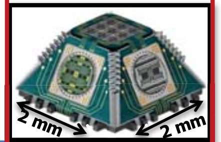
- 20,000 g (survive)
- 1,000 g (operation)
- -54C to +85C
- 40Hz spin

Microtechnology for Positioning, Navigation, Timing

The program addresses the emerging DOD need to:

- Decrease reliance on GPS
- Increase system accuracy
- Reduce co-lateral damage
- Increase effective range
- Reduce SWAP&C

Objective



Parameters	Units	SOA	SOA MEMS	micro-PNT
Size	mm³	1.6x10⁷	6.5x10⁴	8
Weight	gram	4.5x10³	2x10²	~2
Power	Watt	25	5	~1
Gyro Range	deg/sec (Hz)	1,000 (3)	3,600 (10)	15,000 (40)
Gyro Bias	deg/hr	0.02	4	0.01 (0.001)
Gyro ARW	deg/√hr	0.01	0.12	0.001 (0.0001)
Gyro Drift	ppm, 3σ	1	400	1
Accel. Range	g	25	70	1,000
Accel. Bias	mg	0.1	4	0.1 (0.001)
Misalignment	μ-radians, 3σ	200	1,000	100
Short-term Time Loss	ns/min	0.001	100	1
Long-term Time Loss	ns/month	10	N/A	32

Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

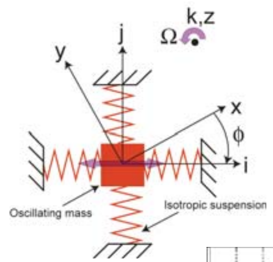
Our Options on Micro Scale

- **Optical** (Sagnac Effect)
  - RLG
    - $\Delta\Phi^{light}_{Sagnac} = 8\pi^2 \frac{R^2}{\lambda_s c}\Omega$
    - Exact cavity, prec. mirrors, gas leakage, 100sV (10W)
  - FOG
    - RFOG narrowband source & cav
    - $\Delta f = \frac{4A}{\lambda_s L n}\Omega$
    - IFOG covers low/medium performance
    - $\Delta f = f_{cw} - f_{cc}$
- **Atomic** (Spin or "Sagnac")
  - ASG on NMR
    - $\omega = \gamma B_0 + \Omega$
    - Magnetic sensor measuring Larmor shift
  - AIG (matter-waves
    - like IFOG but "splitters", "mirrors", detectors are different
    - $\Delta\Phi^{light}_{Sagnac} = 2\pi \frac{2}{\lambda_s c}\Omega$
    - $\Delta\Phi^{atoms}_{Sagnac} = 2\pi \frac{2m_{at}}{\hbar} A\Omega$
    - $\frac{\Delta\Phi^{light}_{Sagnac}}{\Delta\Phi^{atoms}_{Sagnac}} = \frac{m_{at}\cdot\lambda_s\cdot c}{\hbar} \approx 10^{11}$
    - but: !!! $\Delta\Omega(A, S/N)$!!!
- **Mechanical** (gyroscopic effect)
  - Spinning
    - $\Omega = \frac{T}{I\omega}$
    - Large inertia and fast spin. Levitation.
  - Vibrating
    - $y_{sense} = \frac{2Q_s \cdot x_d}{\omega_{drive=sense}}\Omega$
    - Rate gyro: large drive amp, symm
    - $\theta = -\eta\int\Omega\, dt$
    - Whole angle gyro: hard to build, symm

What did and didn't work

- **Didn't**
  - Miniaturization of RLG
    - Unavoidable solid glass optical block and mechanical dither. Miniaturization reduced reliability from 10,000h to ~100h of operation, due to slow leakage of gas, exacting cavity, precision mirrors, stringent clean room conditions
  - Tunneling accelerometer
    - High sensitivity, but drift, large DC noise, migration of atoms, interactive atomic force, mobile absorbed contamination, distribution of electron traps,…
- **Did**
  - HRG (e.g., Delco, SAGEM, Электроприбор)
  - Bulk accelerometers with self-calibration (e.g., SiAc)

Type I & Type II gyroscopes

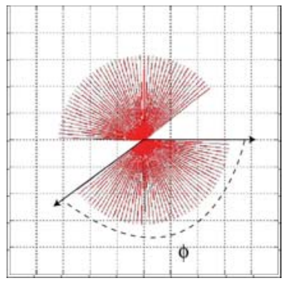


Ideal Type I dynamics

$$\ddot{x} + \omega_n^2 x = 2\Omega\dot{y}$$
$$\ddot{y} + \omega_n^2 y = -2\Omega\dot{x}$$

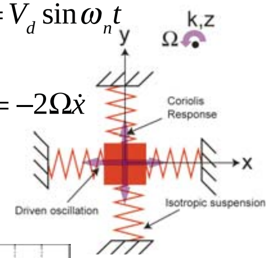
$$\phi = -\eta\int\Omega\, dt$$

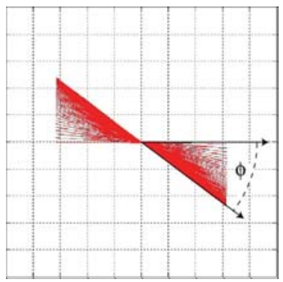
Precession measurement



$$\ddot{x} + \frac{\omega_n}{Q}\dot{x} + \omega_n^2 x = V_d \sin\omega_n t$$
$$\ddot{y} + \frac{\omega_n}{Q}\dot{y} + \omega_n^2 y = -2\Omega\dot{x}$$

Ideal Type II dynamics



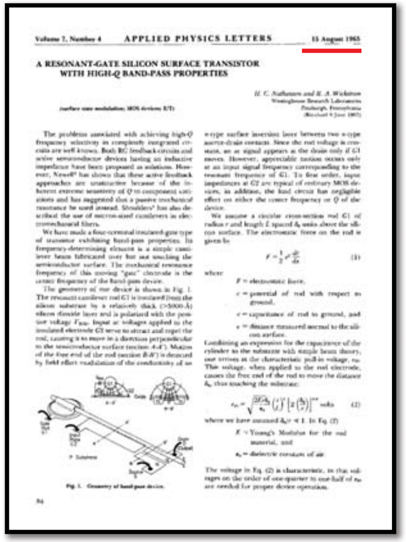


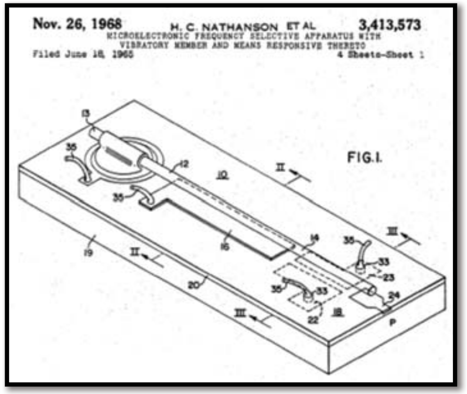
$$|y(t)| = \frac{2X_D Q}{\omega_n}\Omega$$
$$\phi \approx -2\frac{Q}{\omega_n}\Omega$$

Rate measurement

Reference: A. M. Shkel. Type I and Type II Micromachined Vibratory Gyroscopes. In IEEE/ION Position Location and Navigation Symposium (PLANS), pg. 586-593, San Diego, California, USA, 2006.

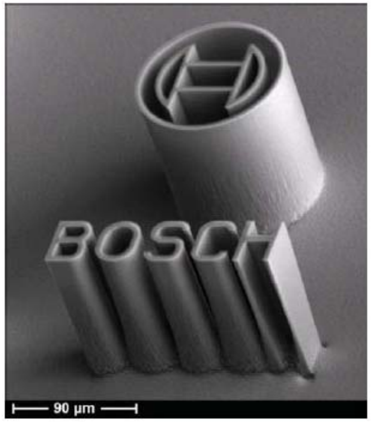
First MEMS devices – 2D





- Problem of high-Q frequency selectivity in IC
- Used active feedback RC circuits & semicond.
- Proposed passive mechanical resonance for Q
- **Harvey C. Nathanson,** et al., **1965**

30 years later – 2.5D



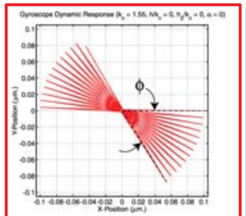
US Patent 5,501,893

- Deviation from bulk wet etching processes
- Not IC-like surface micromachining
- Pulsed isotropic plasma etching & passivation
- High aspect ratio
- **Franz Laermer** and **Andrea Schilp**, **1996**

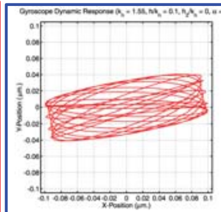
Symmetry is the key

Ideal Dynamics | **Actual Dynamics with Perturbations**

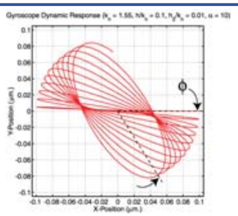
$$\begin{pmatrix}\ddot{x}\\ \ddot{y}\end{pmatrix}+\begin{bmatrix}\omega_n^2 & 0\\ 0 & \omega_n^2\end{bmatrix}\cdot\begin{pmatrix}x\\ y\end{pmatrix}+\begin{bmatrix}0 & -2\Omega_z\\ 2\Omega_z & 0\end{bmatrix}\cdot\begin{pmatrix}\dot{x}\\ \dot{y}\end{pmatrix}=\begin{pmatrix}\alpha_{xx} & \alpha_{xy}\\ \alpha_{xy} & \alpha_{yy}\end{pmatrix}\cdot\begin{pmatrix}x\\ y\end{pmatrix}+\begin{pmatrix}\beta_{xx} & \beta_{xy}\\ \beta_{yx} & \beta_{yy}\end{pmatrix}\cdot\begin{pmatrix}\dot{x}\\ \dot{y}\end{pmatrix}+\begin{pmatrix}\delta_{xx} & \delta_{xy}\\ \delta_{yx} & \delta_{yy}\end{pmatrix}\cdot\begin{pmatrix}f(x,\dot{x})\\ f(y,\dot{y})\end{pmatrix}$$



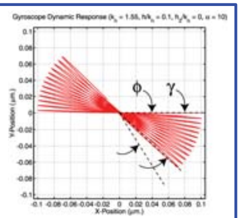
Ideal response



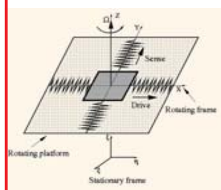
Anisoelasticity

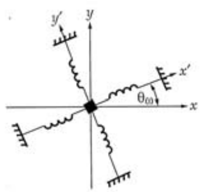


+ rotation



anisodamping





$$\Omega_{err}=\frac{\pi}{Q^2}\left(\omega\Delta_Q+Q\Delta_\omega\right)$$

3D shells on MACRO scale

northropgrumman.com

sagem-ds.com

Advantages of wineglasses
- Dynamically balanced
- Robust to g-forces
- Robust to thermal variations

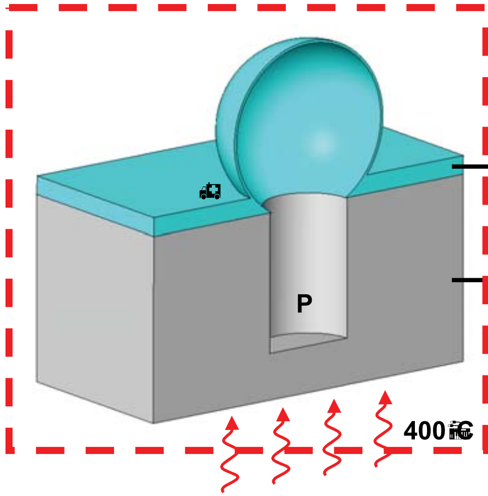
Device specifications
- Q = 25 mil, bias stability < 0.0001 °/hr
- Size > 1 inch
- 50k usd per axis

Extremely high performance, boutique process, outrages cost

3D inspiration

Micro Glassblowing process

US Patent 7694531: Micro-glassblowing of pyrex glass

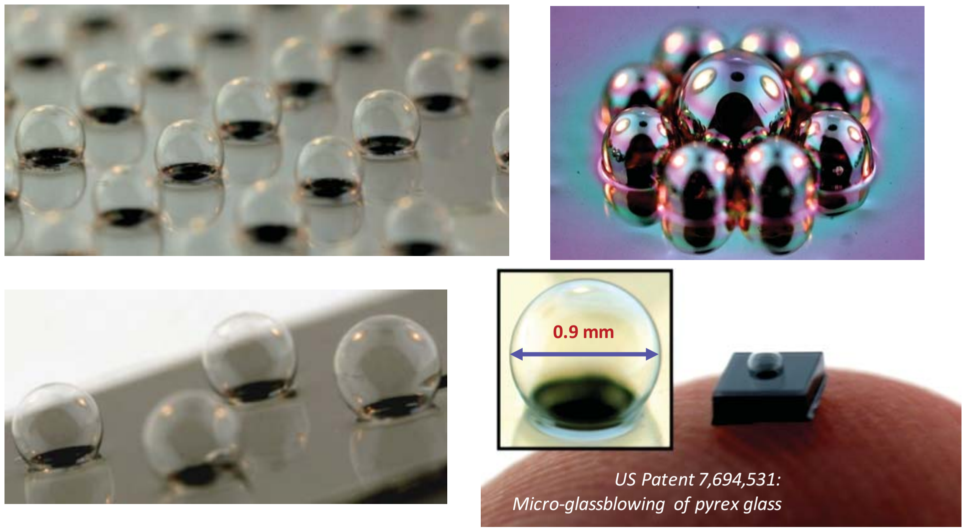


- Etch cavities in silicon wafer
- Anodic bonding
  - 100 µm thick Pyrex 7740 glass
- Place chip in furnace
  - 850 °C (above softening point)
- Remove from furnace
- Anneal to relieve stress
- Fill cells with Rb and Xe (at NIST, Boulder, CO*)

* Knappe, et al., Opt. Lett. 30, pp.2351, 2005

* J. Eklund, A.M Shkel., JMEMS 2007

Wafer-level process



* J. Eklund, A.M Shkel., JMEMS 2007

From Pyrex to Fused Silica

	1	2	3
Pyrex/Si Fabrication	DRIE of silicon	Anodic bonding	850 ºC glassblowing
ULE/FS Fabrication	Deep oxide etching ■ Low mask selectivity ■ Low etch rate	Plasma bonding ■ Requires <1nm Ra ■ Very sensitive to contamination	1700 ºC glassblowing ■ Specialized furnace: ■ High temperature ■ Rapid cooling ■ Most metals melt

1700 ºC glassblowing temperature is required

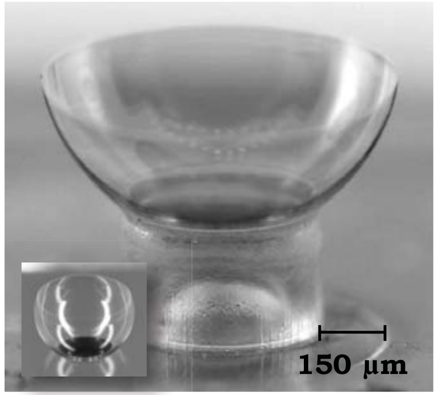
Fabrication Process "A"

Step 1: Etching/Bonding
- Silicon / Pyrex / Silicon
- Simultaneous bonding

Step 2: Glassblowing
- Through the stencil
- 875 °C for ~2 minutes

Step 3: Laser cutting
- Excimer laser ablation
- Along circle of latitude

Step 4: Stem release
- XeF2 etching of stencil
- >2000:1 selectivity

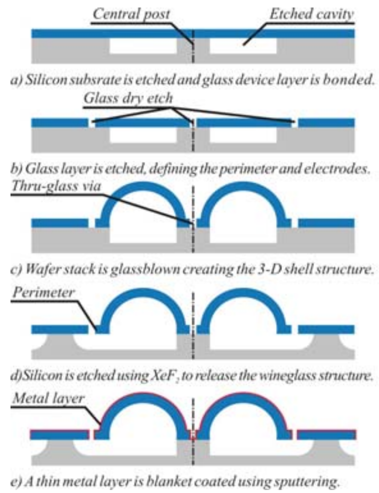


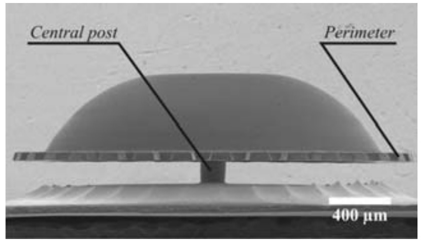
Wineglass with stem

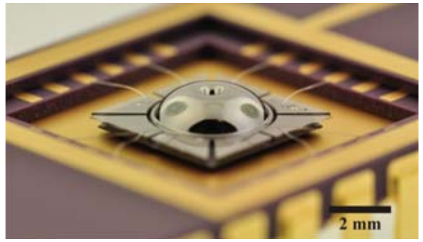
* Published in Technologies for Furure M.Worksop 2011

Issues: Hollow/large diameter stem, requires stencil layer

Fabrication Process "B"



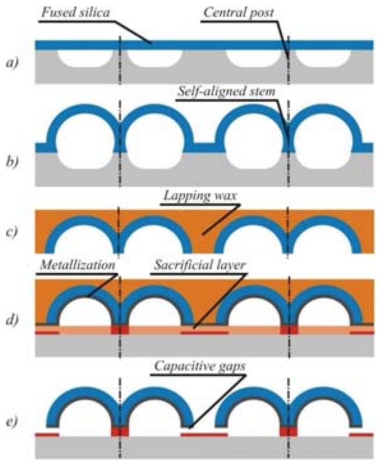


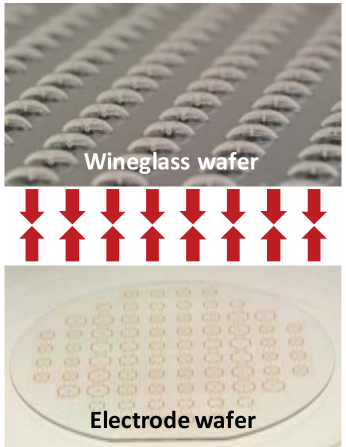


D. Senkal, M.J. Ahamed, A A. Trusov, A M. Shkel,, JMEMS 2013.

Plastic deformation of device layer

Fabrication Process "C"



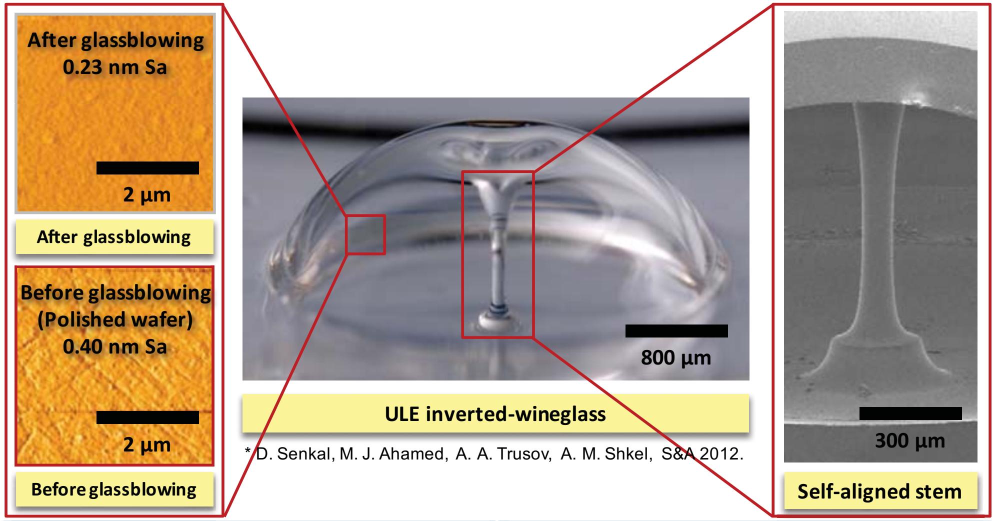


Planar electrodes provide scalability to wafer-level

Batch fabrication

Batch-process ➔ Scalable

Surface quality



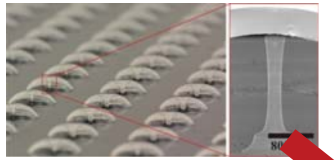
*D. Senkal, M. J. Ahamed, A. A. Trusov, A. M. Shkel, S&A 2012.

Atomic smoothness (0.23 nm Sa) | **Self-aligned < 200 µm stem**

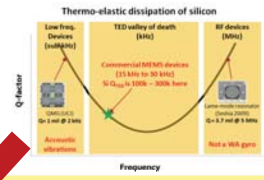
Andrei M. Shkel UCI University of California, Irvine

Understanding Q-factor

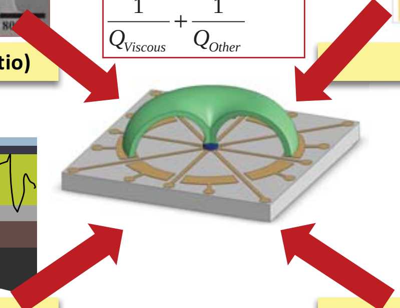
$$\frac{1}{Q}=\frac{1}{Q_{TED}}+\frac{1}{Q_{Anchor}}+\frac{1}{Q_{Elect}}+\frac{1}{Q_{Assym}}+\frac{1}{Q_{Viscous}}+\frac{1}{Q_{Other}}$$

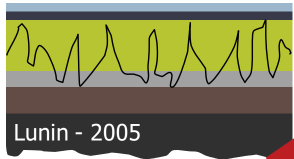


Anchor loss ➔ Stem (1:10 ratio)



TED ➔ Fused silica





Surface losses ➔ Glassblowing

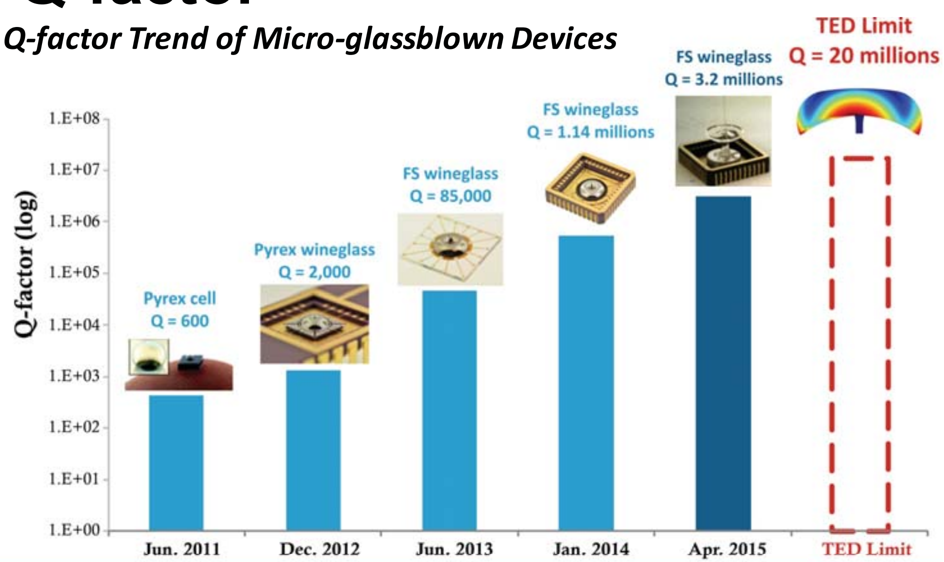
Material losses ➔ High purity

Total Q-factor is determined by the weakest link

Andrei M. Shkel UCI University of California, Irvine

Q-factor

Q-factor Trend of Micro-glassblown Devices



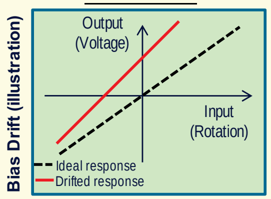
Q-factor is not at TED limit (20M), can be improved further

Andrei M. Shkel UCI University of California, Irvine

DARPA

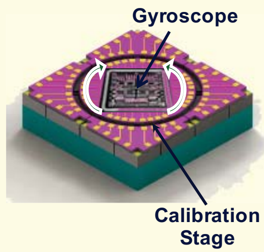
Primary and Secondary Calibration on Active Layer

Motivation



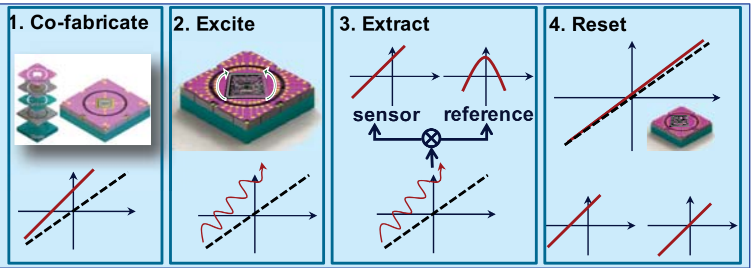
Current options when sensor drifts:
- ❑ Use inaccurate data
- ❑ Remove sensor from system
- ❑ re-calibrate in lab & re-insert in system
- ❑ discard & replace

Approach



Why Now?:
- ❑ Previously, technology pushed towards the "perfect" sensor
  - ❑ community now realizes the challenges of this approach
- ❑ Phenomenon of drift not well understood
- ❑ Re-calibration circumvents knowledge about the cause of drift
- ❑ New emerging technological advances permit the miniaturization of rate tables for on-chip calibration

New Approach:
1. Fabricate sensor directly on calibration stage
2. Periodically apply reference stimulus (e.g. oscillatory)
3. Extract reference stimulus and sensor response
4. Recover new I/O relationship and reset bias



Quadruple Mass Gyroscope

High Quality Factor CVG:

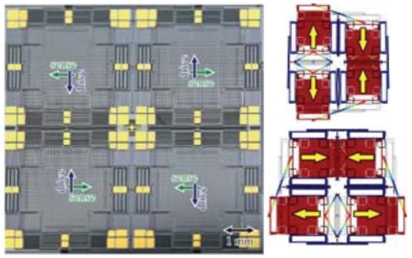
- Dynamically balanced structure
- Anti-phase motion: robust to g-forces
- Zero reaction moment on anchor
- Mode Ordering and Mode reversal

Standing Wave CVG

milli- Hemispherical Resonator Gyroscope

* Patent No.: US 7,839,059 B2

Lumped Mass CVG



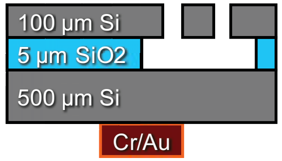
Quad Mass Gyroscope (QMG)

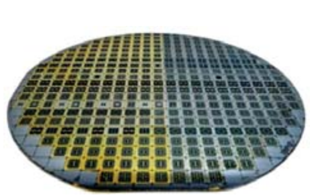
* Patent No.: US 8,322,213 B2
* Patent No.: US 8,991,247 B2

QMG is dynamic analogous to HRG

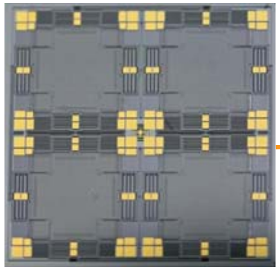
SOI as a platform

- $100\ \mu m$ SOI
- Only 3 masks

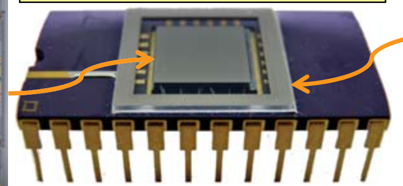




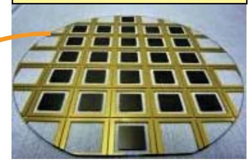
Quad Mass Gyro die



QMG sealed at $0.1\ mTorr$



Getter lid wafer



Flexible platform for academic research on design of sensors

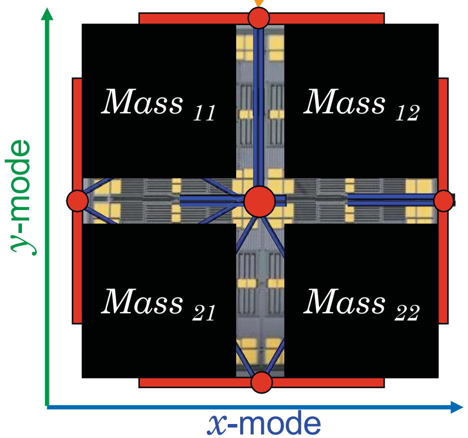
Quad Mass Gyro (QMG)

Design

- 4 anti-phase tines
- 20 sync. levers

Features

- Symmetric f and Q
- Angle gain of 0.9
- $Q_{TED} > 1{,}000{,}000$
- 0.0001 °/$\sqrt{hr}$ limit



Sophisticated design of multi-DOF system on a simple SOI platform

**Trusov, Schofield, Shkel, US Patent 8,322,213*

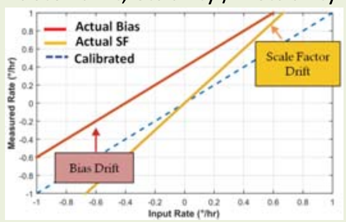
DARPA **Current results: Algorithmic Development** UCIRVINE NORTHROP GRUMMAN

Continuous self-calibration is essential!!

Problem

Bias and Scale Factor drift, stability / instability

- ❑Short term
- ❑Long term
- ❑Run to run



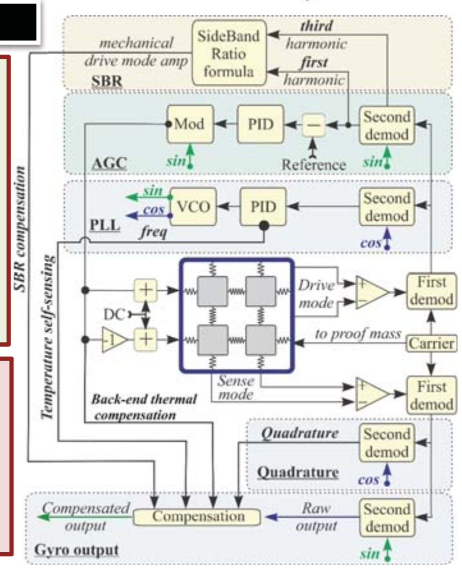
Approach

Control loops

- Phase control
- Amplitude control
- Rate control
- Quadrature control

Calibration stages

- Thermal self-sensing
  - PLL (front-end)
  - AGC (back-end)
- Side-Band-Ratio
- Mechanical Quadrature



Implemented Continuous Self-Calibration Algorithms

Current results: Electronic Platform

UCIRVINE
NORTHROP GRUMMAN

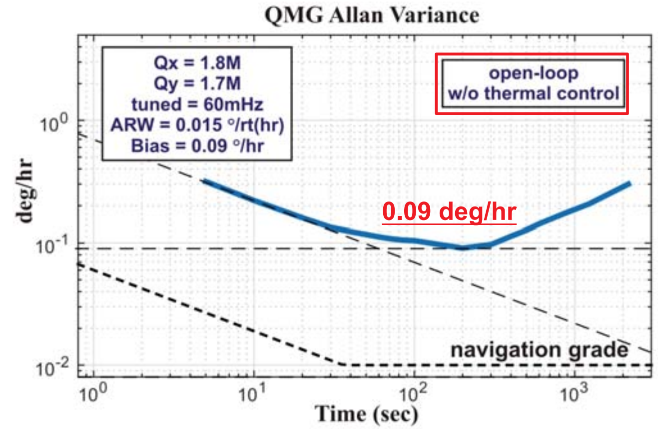
Loops:
- Rate mode,
  - PLL
  - AGC
  - RCA
  - QCA
- Whole Angle
- Mode Reversal,
- Virtual Carouseling
- Self calibration

Interface:
- DARPA PALADIN

PALADIN-compatible control and characterization platform

Current Results: Near-Nav Grade QMG Performance

UCIRVINE
NORTHROP GRUMMAN



Recent lab test	
ARW	0.015 deg/rt-hr
Bias floor	0.09 deg/hr

Government test	
ARW	0.0562 deg/rt-hr
Bias floor	0.2 deg/hr

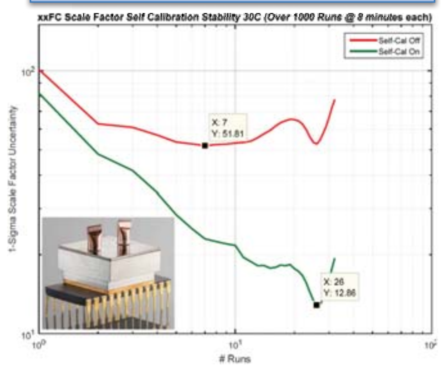
Demonstrated near-Navigation grade in-run ARW and bias floor

Current results: Whole Angle Mode Performance

UCIRVINE
NORTHROP GRUMMAN

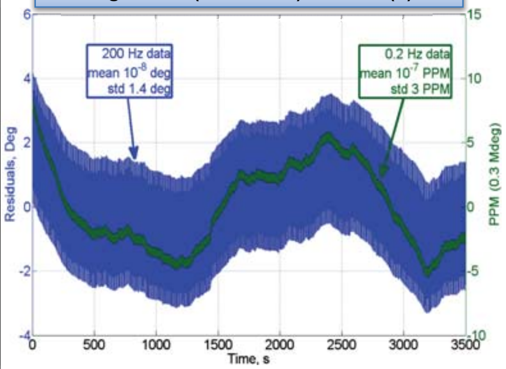
- Scale Factor **self-calibration** stability
- Pattern angle modulation

Scale factor stability <20 ppm



- **1 hr** at **100 °/s** for **.3E6 °**
- All closed loop operation

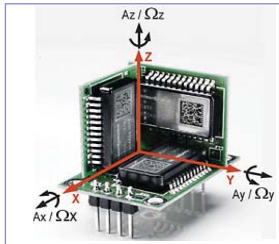
Angle error (° and PPM) vs. time (s)



Whole Angle demo with 3 PPM error @18,000 °/s range.

Approaches for miniature Multi-axis Timing and Inertial Measurement Unit (TIMU)

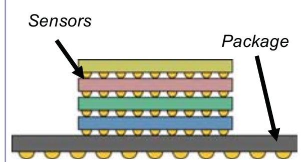
Discrete assembly



(+) High performance single-axis sensors

(-) Large size

Stacked Chips



(+) Reduced footprint

(-) Bonding process Vacuum packaging

Single-chip

(+) Small volume

(-) Compromised performance of in & out-of-plane devices

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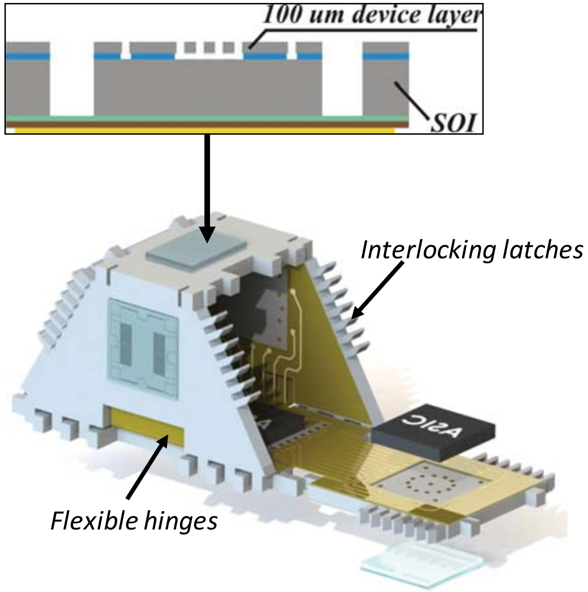
Innovative Claims



1. Batch fabrication

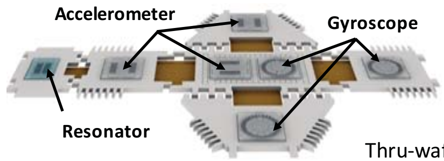
2. Small volume

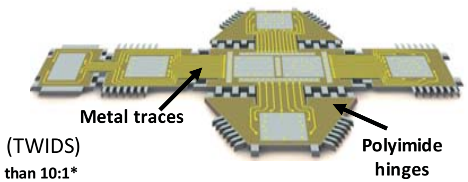
3. High Sensitivity
High aspect ratio single-axis sensors

Silicon origami-like approach

Device Side

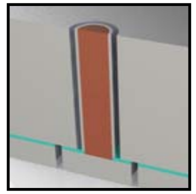
Signal Processing Side





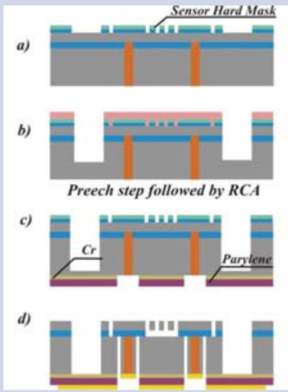
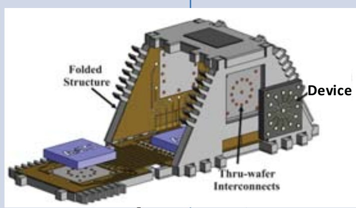
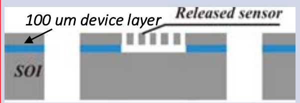
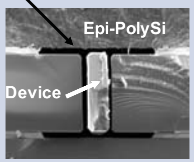
Thru-wafer via (TWIDS)

Aspect ratio better than 10:1*



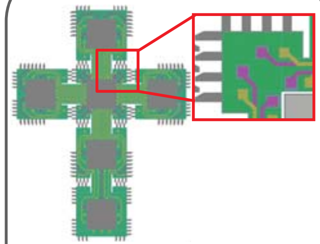
- A. Efimovskaya, D. Senkal, A. M. Shkel, IEEE Transducers 2015 Conf., Alaska, USA, June 21-25, 2015.
- A. Efimovskaya, D. Senkal, S. Askari, A. M. Shkel, IEEE ISISS 2015, Hawaii, USA, March 23-26, 2015.
- A. Trusov, M. Rivers, S. Zotov, A. M. Shkel," Three dimensional folded MEMS technology for multi-axis sensor systems", US Patent 8368154 B2.
- A. Efimovskaya, Y. Lin, and A. M. Shkel, "THRU-Wafer Interconnects for Double-Sided (TWIDS) Fabrication of MEMS", IEEE Inertial Sensors, 2016.
- A. M. Shkel and A. Efimovskaya "Thru-Wafer Interconnects for MEMS Double-Sided Fabrication Process (TWIDS)", UC CASE N° 2015-218-2.
- A. Efimovskaya, D. Senkal, and A. M. Shkel, "A Low-cost Wafer-level Process for Packaging MEMS 3-D Devices", UC CASE N° 2015-807-1.

Technical Approach

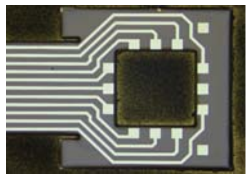
1) In-situ fabrication	2) Integrated with "in-house" devices	3) Integrated with Epi-Seal devices
	 	
SOI sensors and parylene hinges	"In-house" SOI process	EpiSeal proces

Technology potential

1. Processing

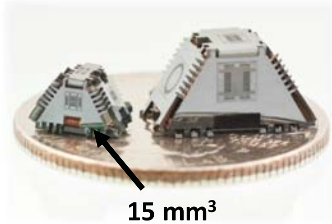


2-Layer metal traces for sensor area optimization

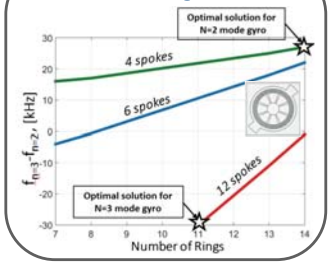


Contact Pads Reinforcement

Folded MEMS TIMU

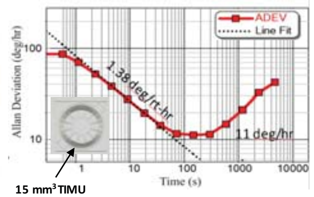


2. Design

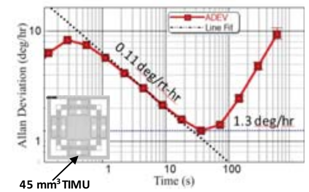


3. Characterization

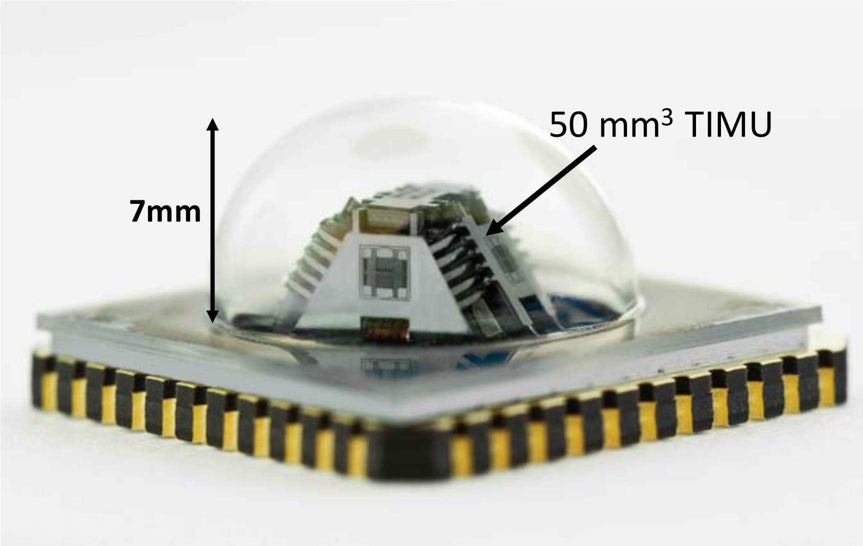
Toroidal Ring Gyro (TRG)



Dual Foucault Pendulum (DFP) Gyro



Origami-like 3D MEMS Technological Platform



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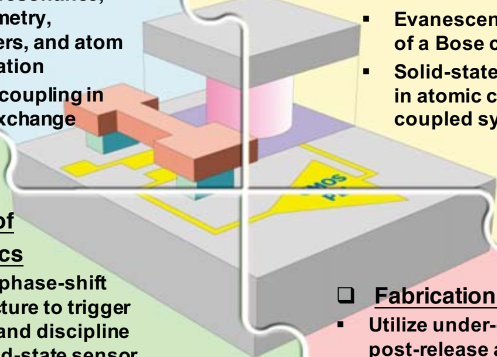
DARPA **C**hip-**S**cale **C**ombinatorial **A**tomic **N**avigator (C-SCAN)

Utilize ensemble of technologies to increase precision and sample rate

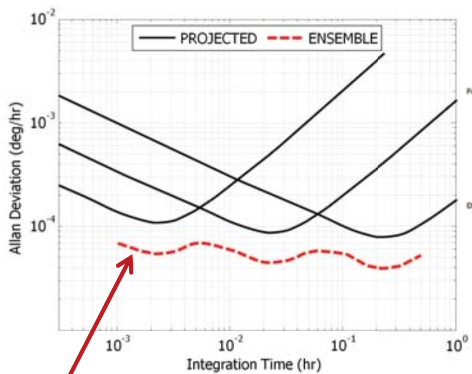
- **Ultra-miniaturization of atomic inertial sensors**
  - Harness energy transitions in nuclei magnetic resonance, atomic interferometry, hyperfine transfers, and atom number amplification
  - Exploit inherent coupling in polarized spin-exchange
- **Multi-functional microsystem**
  - Atomic clocks as a frequency reference for frequency modulated sensors.
  - Evanescent wave confinement of a Bose condensate
  - Solid-state devices integrated in atomic cells, feed-back coupled systems

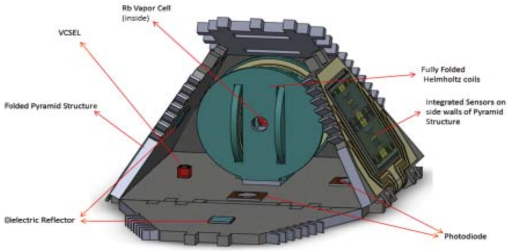


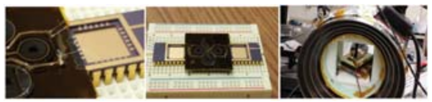
- **Combinatorics of dissimilar physics**
  - Develop zero net phase-shift coupling architecture to trigger atomic emission and discipline less accurate solid-state sensor
  - Adapt optimal estimators for bias adjustment and compensation
- **Fabrication processes**
  - Utilize under-explored processes: post-release assembly, chip-level welding
  - 3D fabrication and assembly processes: blow, stretch, stamp, roll

Approved for Public Release, Distribution Unlimited

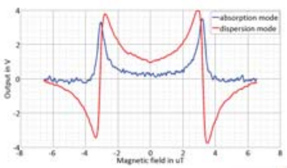
UCI Chip-Scale Combinatorial Atomic Navigator (C-SCAN)







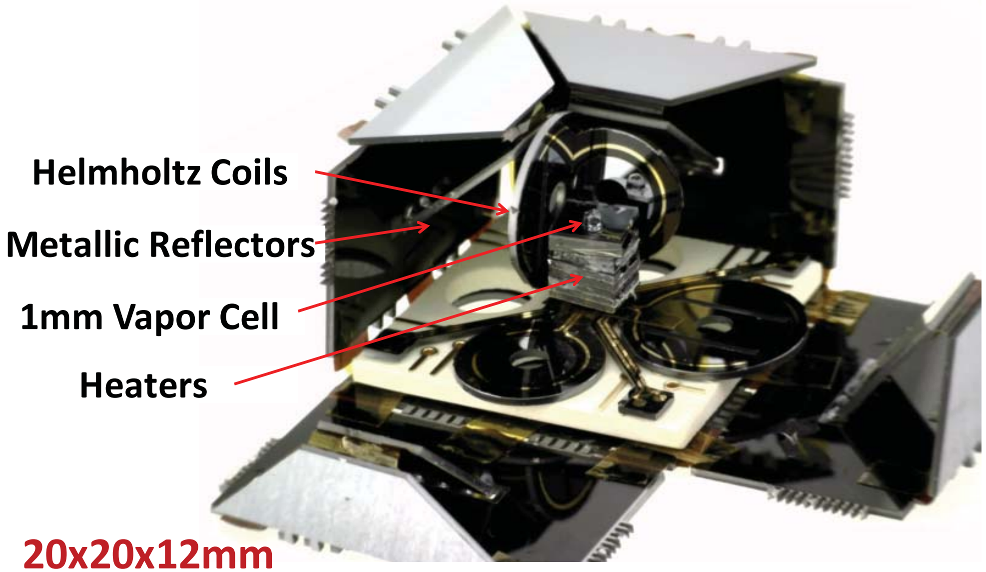
Ensemble of gyros are predicted to produce a system with noise characteristic 10^2 lower than any single consistent inertial sensor



Results
Line-width ~= 130nT,
Sensitivity ~= 150pT/√Hz

MICROSYSTEMS

Atomic microsystems



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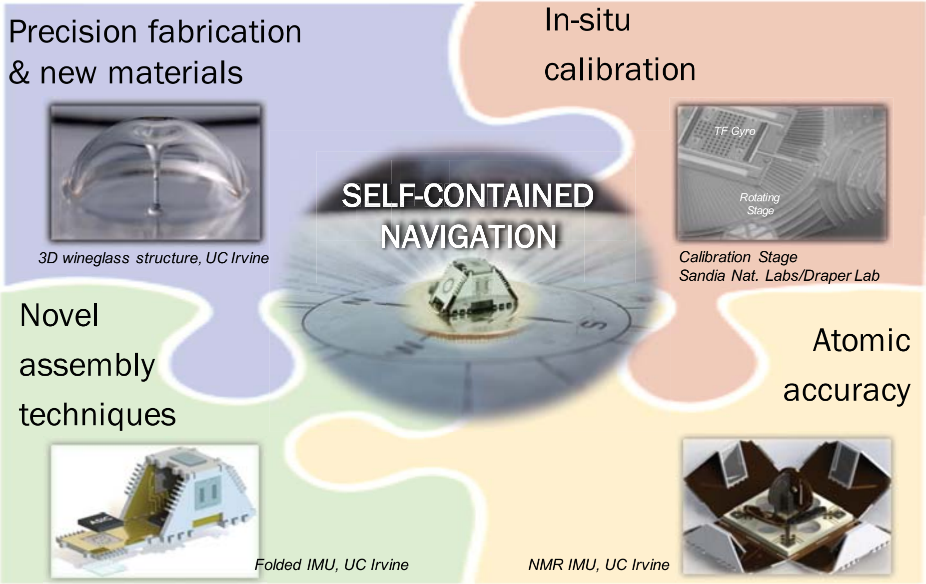
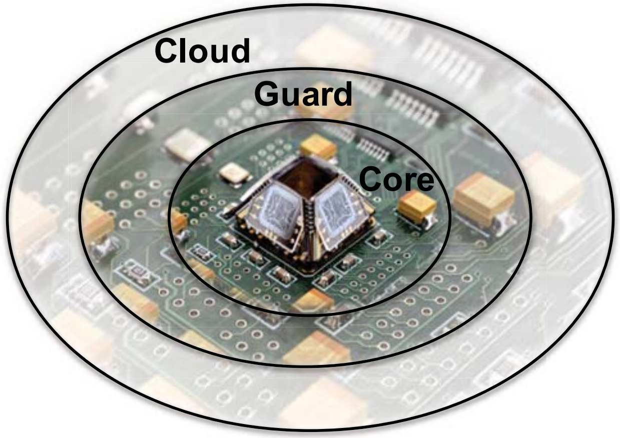
Path to the Future



If I were to guess …

Ultimate Navigation Chip (uNavChip)



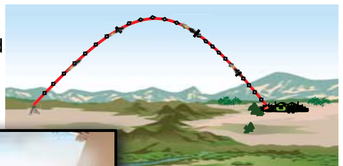
- **Core**
  Timing and Inertial Measurement Unit
- **Guard**
  Authenticate external signals of opportunity
- **Cloud**
  Detect external signals of opportunity

Provide maximum autonomy, security, precision

Enabled by precision

Military

Self-contained navigation



Far-Target detection
North-finder

Navigation of dismounts

Consumer & Industrial

- Geolocation
- Stabilization
- Precision timing

Spoofing

Encryption

Stabilization

Acknowledgement

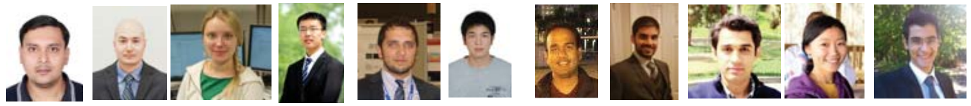
- DARPA
  - Micromachined Rate Integration Gyroscopes (**MRIG**)
  - Primary and Secondary Calibration on Active Layer (**PASCAL**) with Northrop Grumman
  - Timing and Inertial Navigation Unit (**TIMU**)
  - Chip-Scale Combinatorial Atomic Navigator (**CSCAN**)
  - Precise Robust Inertial Guidance for Munitions: Advanced Inertial Micro Sensors (**PRIGM: AIMS**)

Research consumes $ to create ideas, innovation consumes ideas to create $

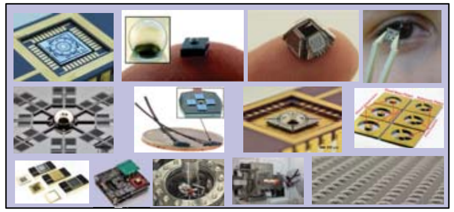
www.ieee-inertial.org

Contact information

Email: andrei.shkel@uci.edu
Phone: (949) 824-3843
http://mems.eng.uci.edu
(for publications, IP, projects)



Microsystems Laboratory
Mechanical and Aerospace Engineering
4202 Engineering Gateway
University of California, Irvine
Irvine, CA 92697-3975



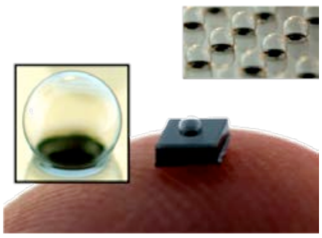
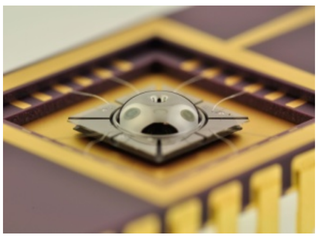
MEMS ジャイロスコープの世界的第一人者 Andrei M. Shkel 教授による特別セミナー
Special Seminar by Prof. Andrei M. Shkel, The world-leading expert in MEMS gyroscopes

日　時：2016 年 5 月 13 日（金曜日）　13:00～15:00
13 May 2016 (Friday)　13:00～15:00
参加無料，事前申込不要　Admission free, No advanced registration required
場　所：東北大学　青葉山キャンパス　マイクロ・ナノマシニング研究教育センター　3 階　セミナー室
Tohoku University, Aobayama Campus, Micro-Nanomachining Research & Education Center (MNC), 3rd floor, Seminar room
（田中(秀)研究室ウェブサイト「アクセス」ページの地図上 A14 の建物）
（Building A14 on the map at http://www.mems.mech.tohoku.ac.jp/access/）
主　催：田中(秀)研究室，マイクロ・ナノマシニング研究教育センター
Organized by S. Tanaka Laboratory and MNC, Tohoku University

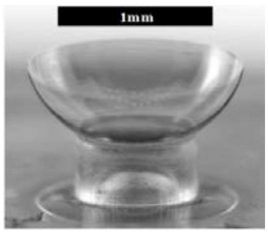
講　師：
Prof. Andrei M. Shkel
Department of Mechanical and Aerospace Engineering, University of California, Irvine

Dr. Andrei M. Shkel has been on faculty at the University of California, Irvine since 2000. From 2009 to 2013, he was on leave from academia serving as a Program Manager in the Microsystems Technology Office of DARPA. Dr. Shkel has been on a number of editorial boards, most recently as Editor of IEEE/ASME Journal of MicroElectroMechanical Systems (JMEMS) and the founding chair of the IEEE Inertial Sensors conference (INERTIAL). Dr. Shkel is the IEEE Fellow. He has been awarded in 2013 the Office of the Secretary of Defense Medal for Exceptional Public Service, the 2009 IEEE Sensors Council Technical Achievement Award, and the 2005 NSF CAREER award. He received his Diploma (1991) in Mechanics and Mathematics from Moscow State University, Ph.D. degree (1997) in Mechanical Engineering from the University of Wisconsin at Madison, and experienced postdoc (1999) at Berkeley Sensors and Actuators Center (BSAC).

要　旨：
After briefly reviewing the fundamentals of MEMS gyroscope, the state-of-the-art MEMS gyroscope technology is introduced. The performance of MEMS gyroscopes are continuously improving to reach the navigation grade, which has been conventionally achieved only by optical gyroscopes. Various types of precise MEMS gyroscopes and advanced control systems developed by Prof. Shkel's Laboratory are presented, including a quad mass gyroscope, a micro hemispherical resonator gyroscope (HRG), and origami-like 3D assembly of MEMS gyroscopes. In addition, this talk touches on novel atomic MEMS for ultra-precise timing reference and magnetic sensing. After this seminar, the attendee can understand that MEMS technology can further extend its sensing precision beyond the present level.





【予習資料】
田中(秀)研究室ウェブサイト「インターネット記事」のページ
・ State-of-the-art MEMS Gyroscopes for Autonomous Cars
・ チップ上にフーコー振子 ― 高性能 MEMS ジャイロ　自動運転などに向けて開発が進む
・ MEMS はもうかる　「IEEE MEMS 2016」学会報告