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Inertial MEMS Sensors are Becoming 3D and Atomically Precise

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The Ancient Problem

18th – 19th century

Sextant

Astrolabe

Back-staff

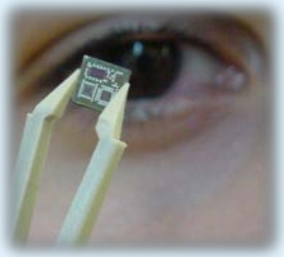
Harrison clock 4

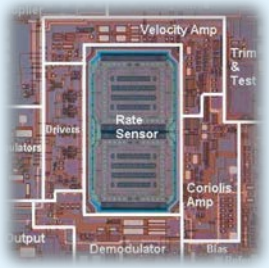
20th century

Autopilot Gyroscope

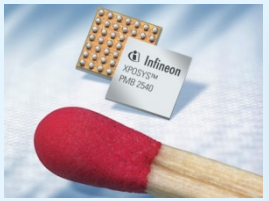
First 5 channel GPS

21st century

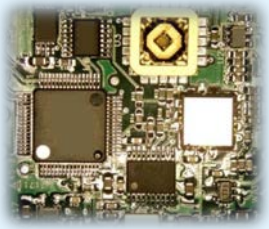




Chip-scale gyroscopes

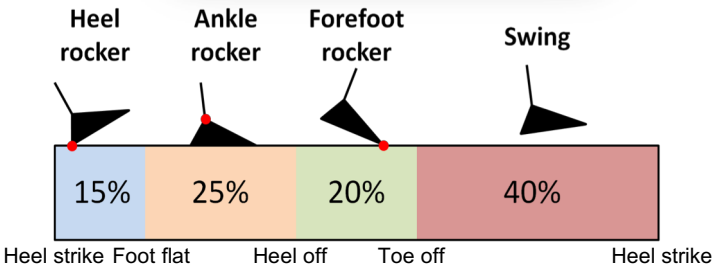


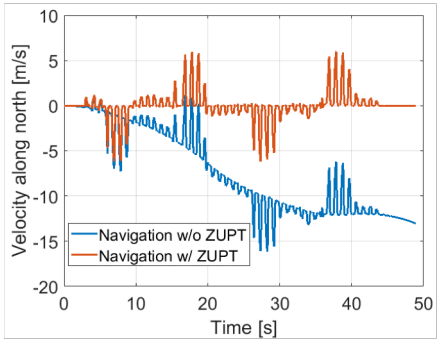
GPS chip

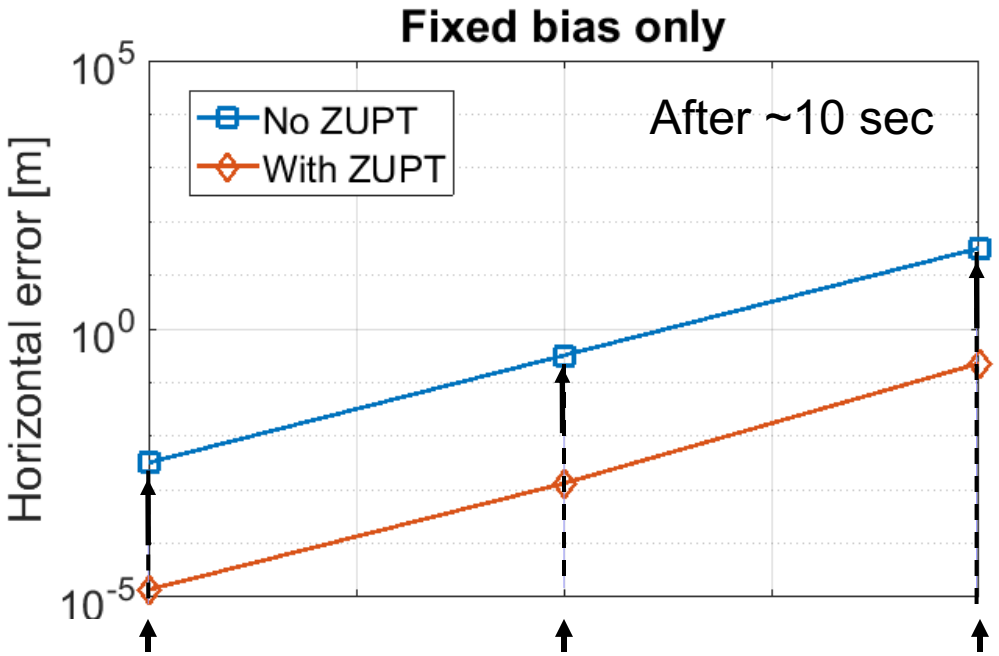


Chip-scale atomic clocks

Navigation of dismounts







Nav grade	Tactical grade	Consumer grade
(0.01 deg/h)	(1 deg/h)	(100 deg/h)
Error Accumulation		
0.05 [m]	**0.5 [m]**	**100 [m]**
0.0001 [m]	**0.001 [m]**	**0.5 [m]**

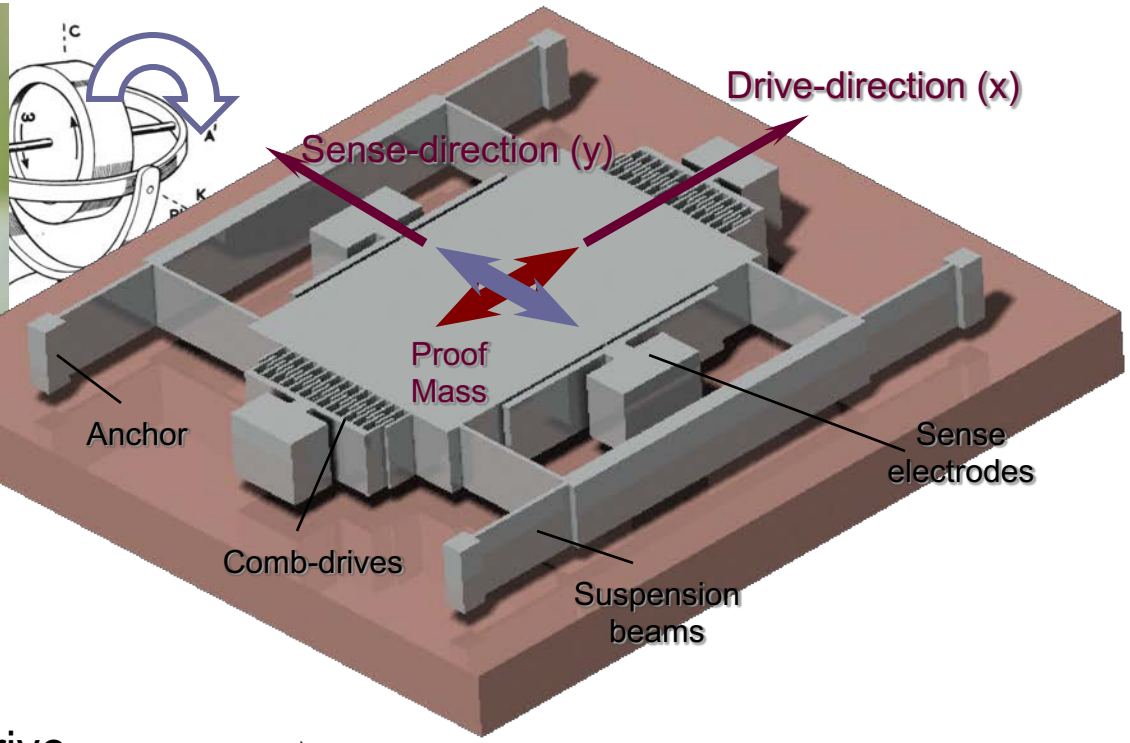
COTS technology (MEMS)

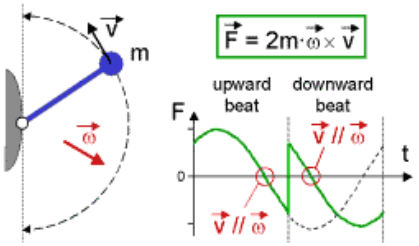
	ADI	Bosch	TDK	STMicro
Part #	ADIS16497	BN0055	MPU-9250	LSM6DS3H
DOF	6	9	9	6
Range (dps)	125 - 2000	2000	2000	2000
Noise (dps/rt-Hz)	0.0015-0.003	0.014	0.01	0.006
In-run bias (dph)	0.8 – 3.3	TBD	TBD	TBD
Package size (mm)	47x44x14	3.8x5.2x1.1	3x3x1	2.5x3x0.83
1k price ($)	1500	7	5	~5

Others: Maxim, Quatre, Fairchild, SSS, Murata, Kionics, …

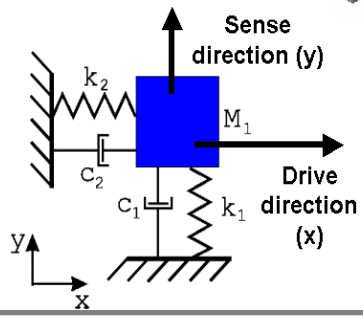
- **Growing** number of suppliers
- **Increased** level of integration & miniaturization
- **Trade-offs**: performance vs. size vs. cost

Conventional MEMS Gyros





- Operate at *resonance* in drive and sense modes.
- *Match* drive and sense resonant frequencies.

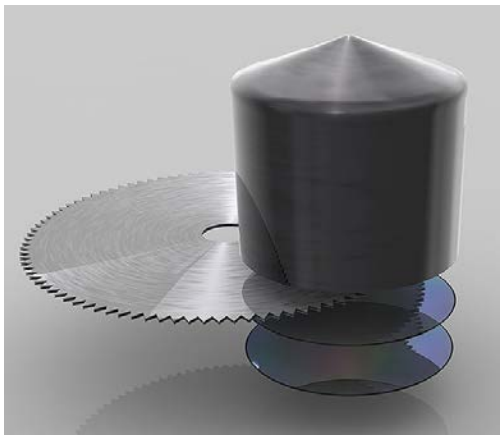


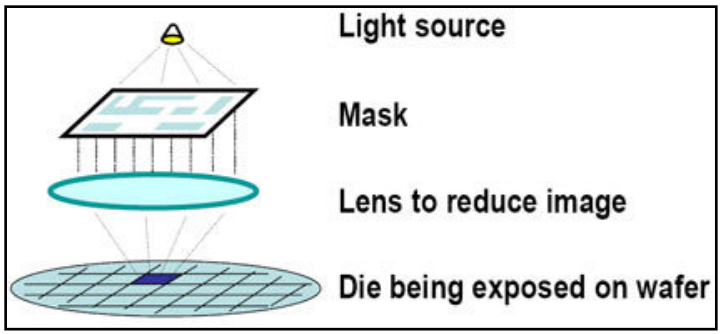
Coriolis Force

$$m\ddot{x} + c_x\dot{x} + k_x x = F_o \sin \omega t,$$

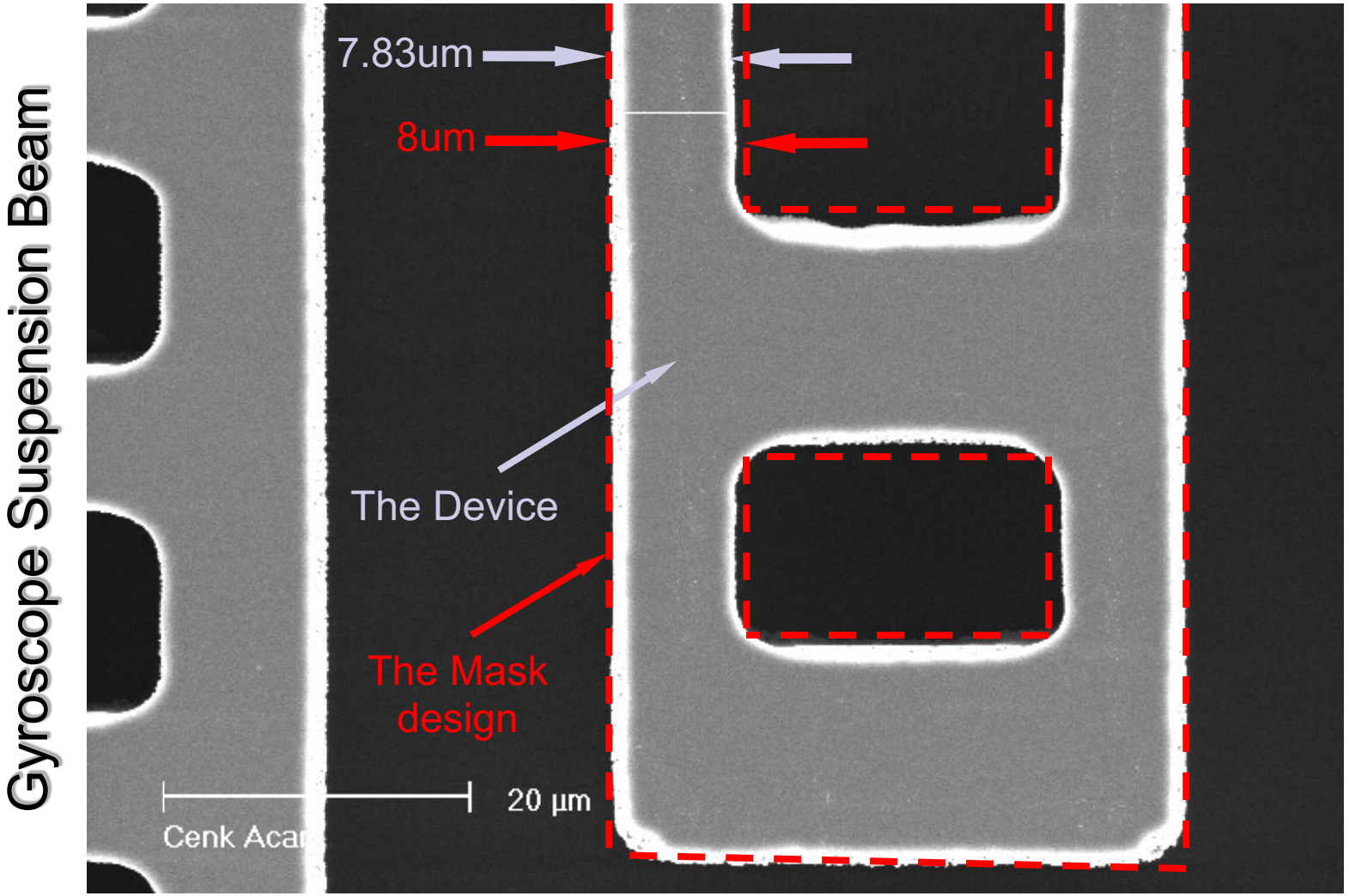
$$m\ddot{y} + c_y\dot{y} - 2m\Omega\dot{x} + k_y y = 0$$

Microfabrication





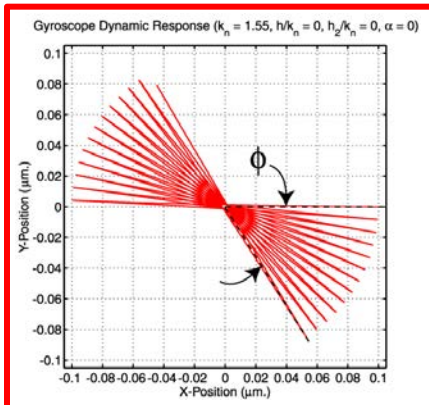
Challenges



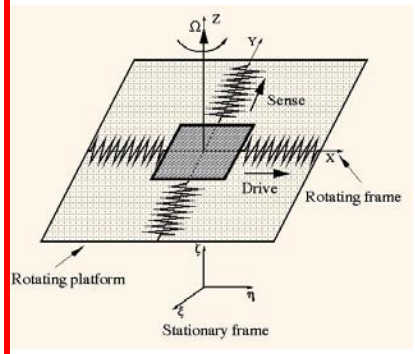
Symmetry is the key: $\Delta\omega$ ΔQ Q

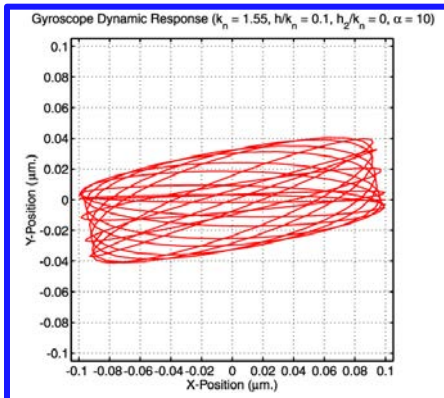
Ideal Dynamics | **Actual Dynamics with Perturbations**

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

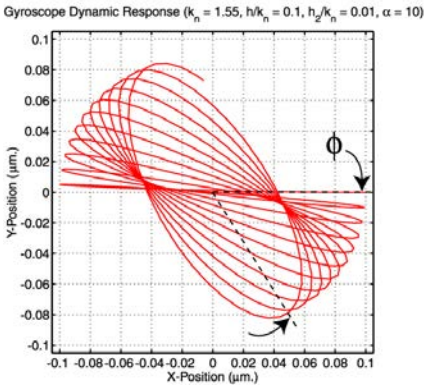


Ideal response

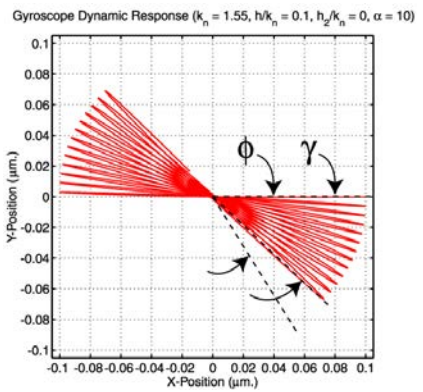




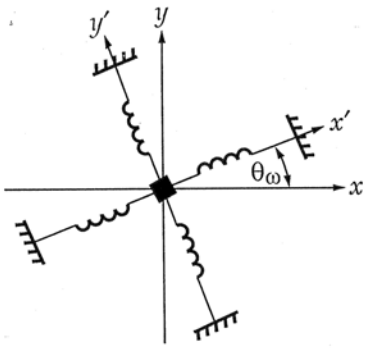
Anisoelasticity



+ 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

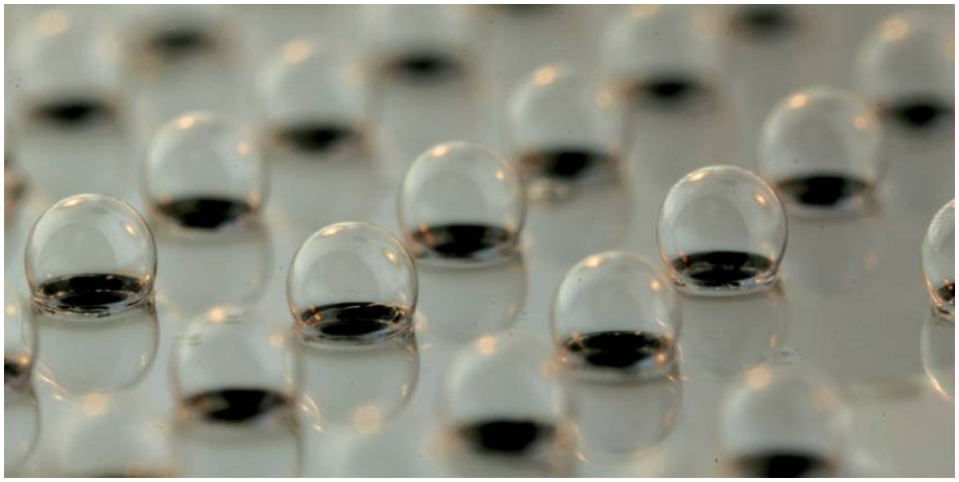
$\Delta\omega$ and ΔQ and Q

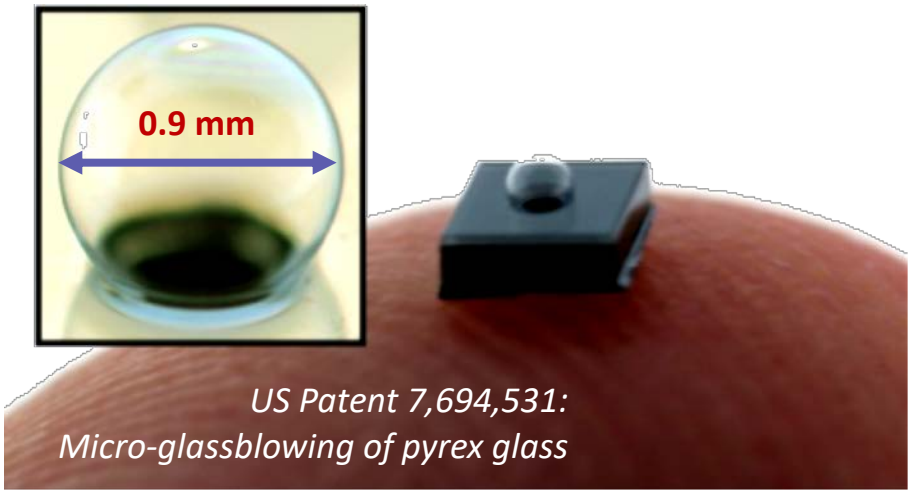
- **Fabrication**
- **Materials**
- **Designs**

- … Multiphysics interactions, vacuum packaging, MIMO identification techniques, non-trivial control electronics

3D inspiration

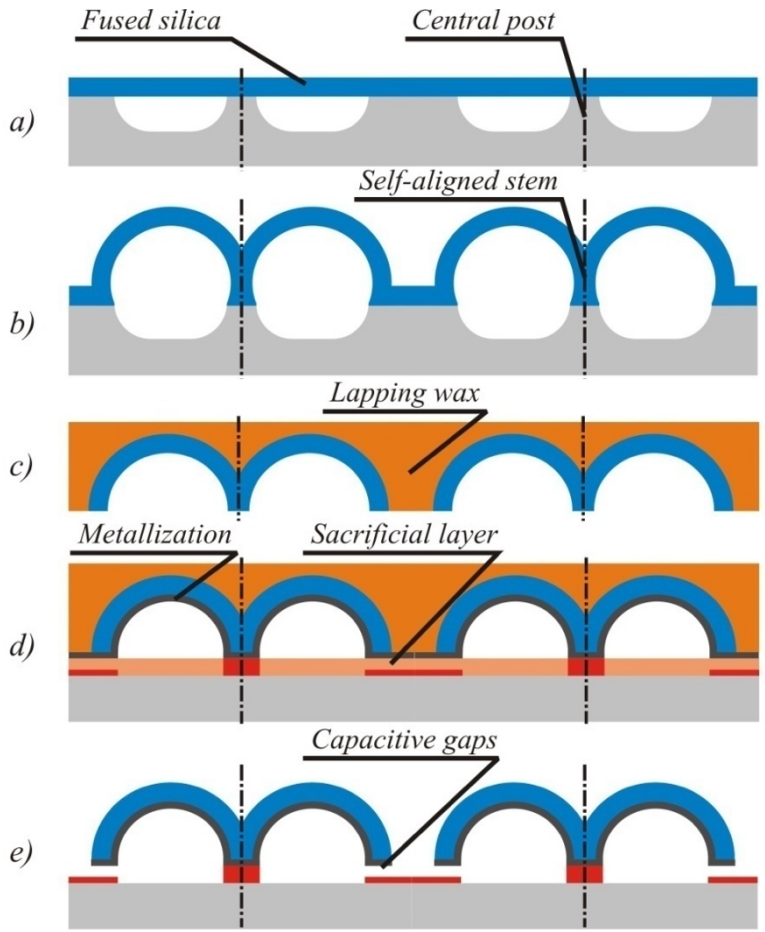
Wafer-level process



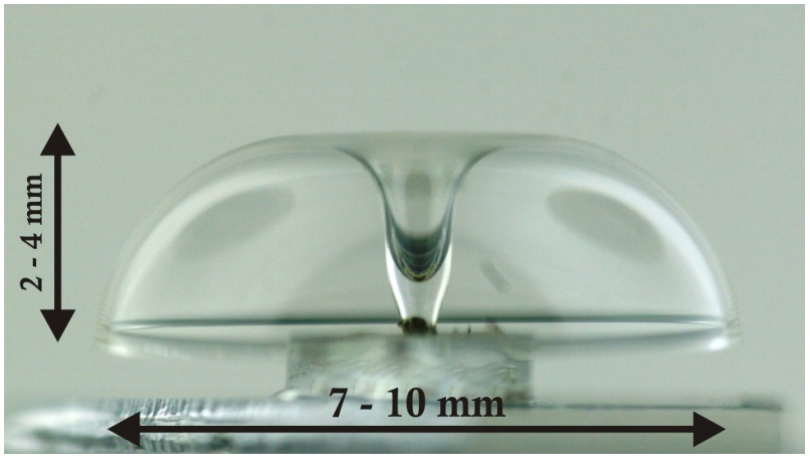


* J. Eklund, A.M Shkel., JMEMS 2007

Micro-glassblowing of FQ shells



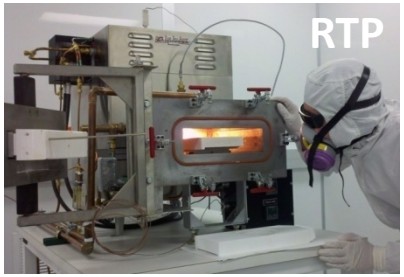
* Senkal, D. et al., Hilton Head, 2014

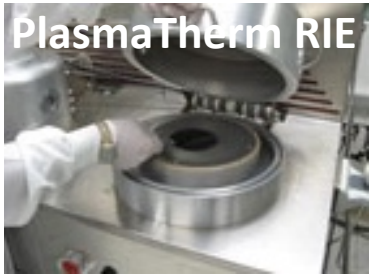


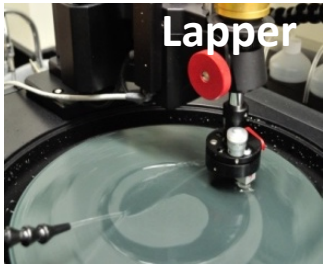
- Low internal loss materials
- Self-aligned anchor
- Axially symmetric
- High-surface quality
- Scalable to wafer-level

3D inverted wineglass FQ shell fabricated by high-temperature glassblowing

Batch fabrication







Batch-process → Scalable

Flat is not dead

High Quality Factor CVG:

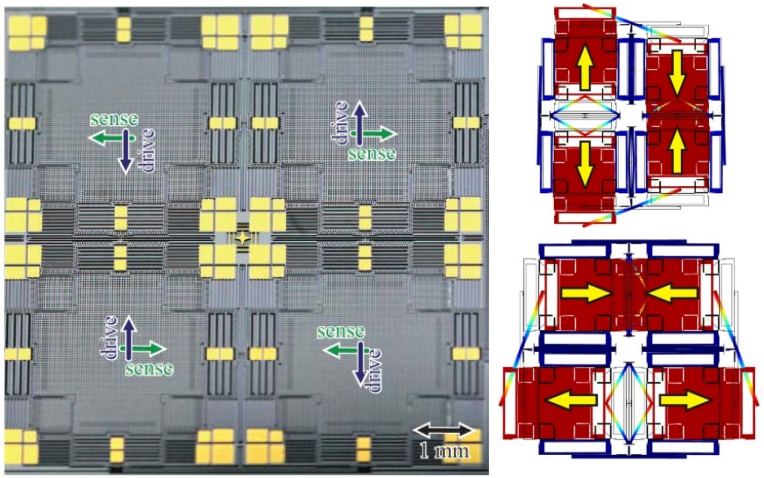
- Dynamically balanced structure
- Anti-phase motion: robust to g-forces
- Zero reaction moment on anchor
- Mode Ordering and Mode reversal

Standing Wave CVG

milli- Hemispherical Resonator Gyroscope

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

Lumped Mass CVG



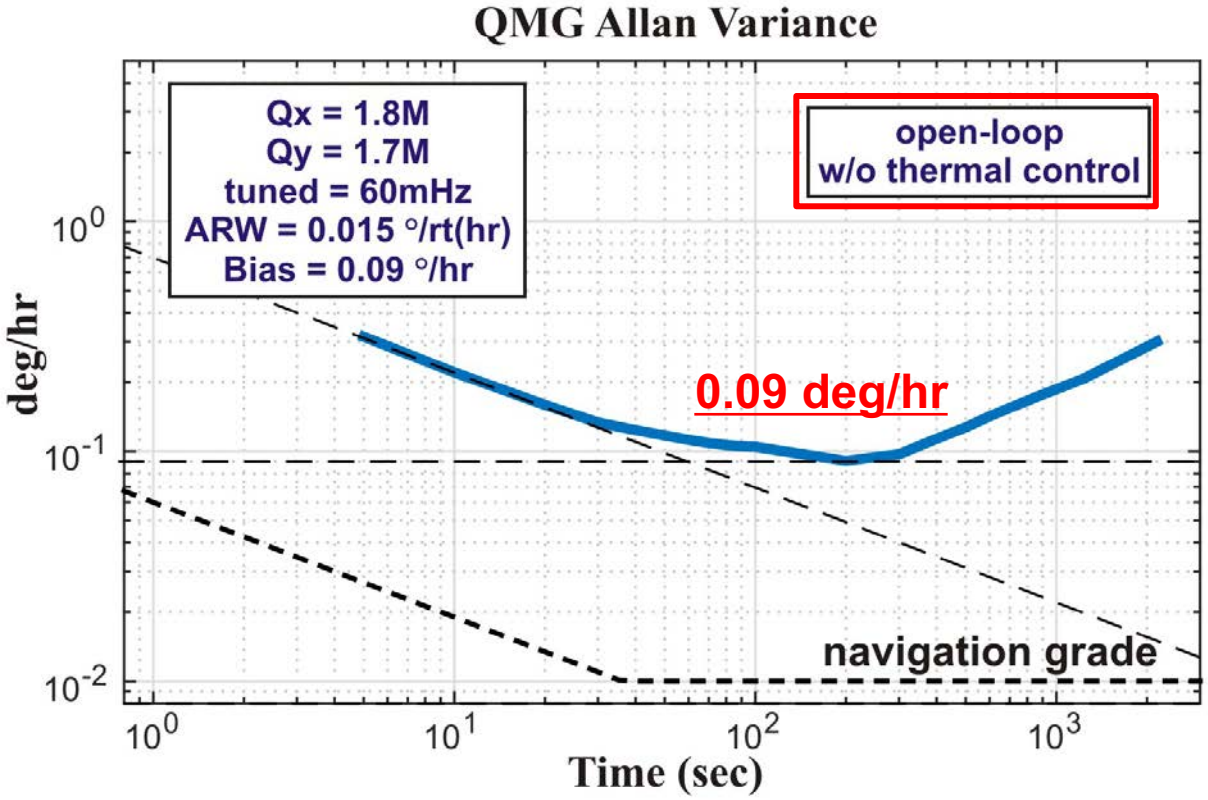
Quad Mass Gyroscope (QMG)

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

QMG is dynamically analogous to HRG

Current Results:

Near-Nav Grade QMG Performance

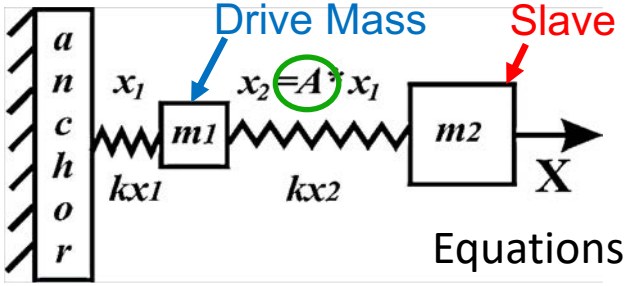


Recent lab test	
ARW	0.015 deg/rt-hr
Bias floor	0.09 deg/hr

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

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

Amplitude Amplified Gyroscope

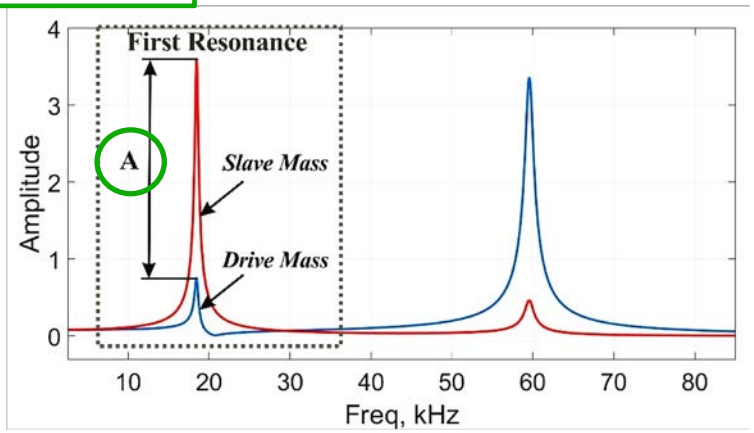


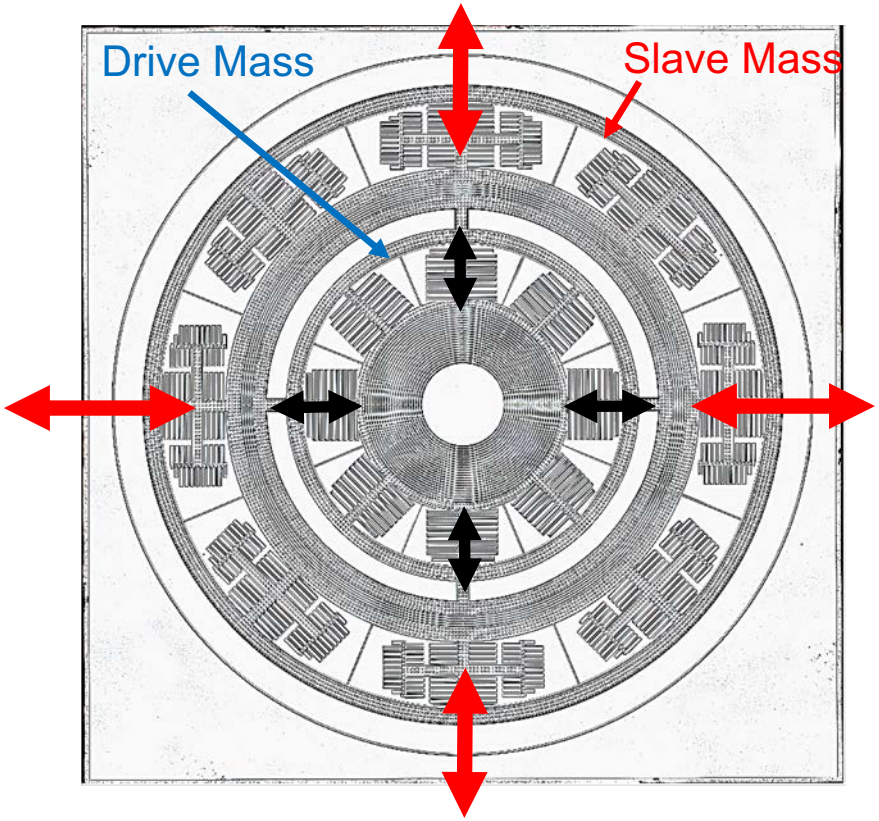
Equations of motion:

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + (k_{x1+}k_{x2})x_1 - k_2x_2 - 2m_1\,\Omega\dot{y}_1 = F_X$$

$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_{x2}x_2 - k_{x2}x_1 - 2m_2\,\Omega\dot{y}_2 = 0$$

$$A = \frac{k_{x1} * m_2}{k_{x2} * m_1}$$

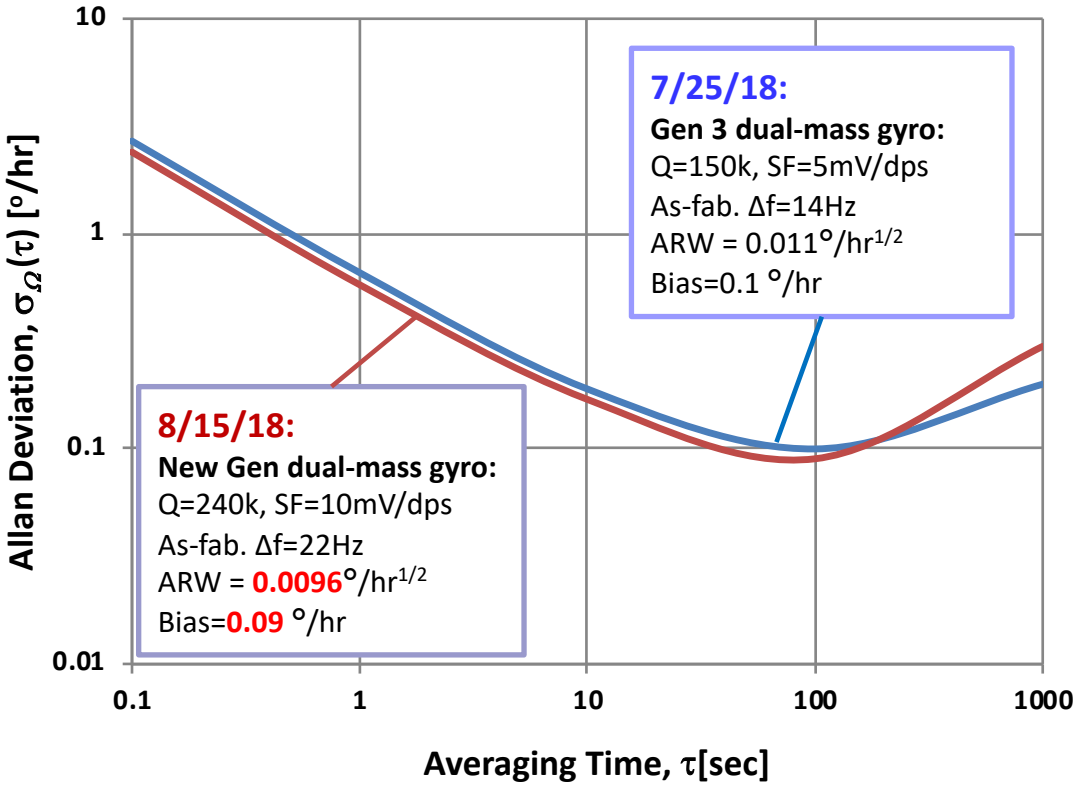




U.S. Patent 6,934,660

- "Drive mass": small amplitudes and linear regime
- "Slave mass": amplified amplitude for enhanced sensitivity

Current Results:
Amplitude Amplified Gyroscopes



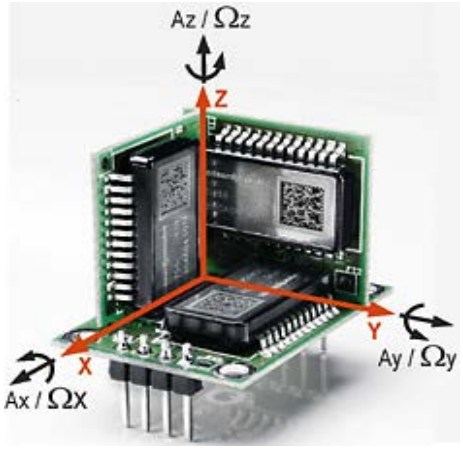
Recent lab test	
ARW	0.0096 deg/rt-hr
Bias floor	0.09 deg/hr

Projected (12m)	
ARW	0.001 deg/rt-hr
Bias floor	0.01 deg/hr

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

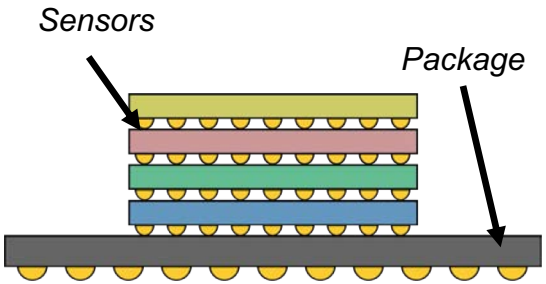
Timing and Inertial Measurement Unit (TIMU)

Discrete assembly



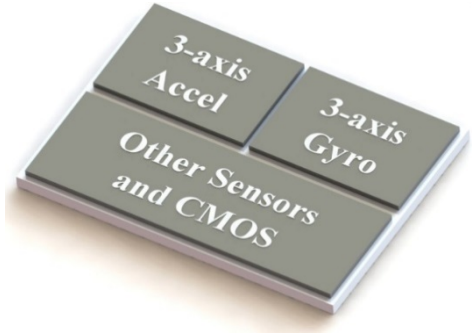
- \+ High performance single-axis sensors
- \- Large size

Stacked Chips



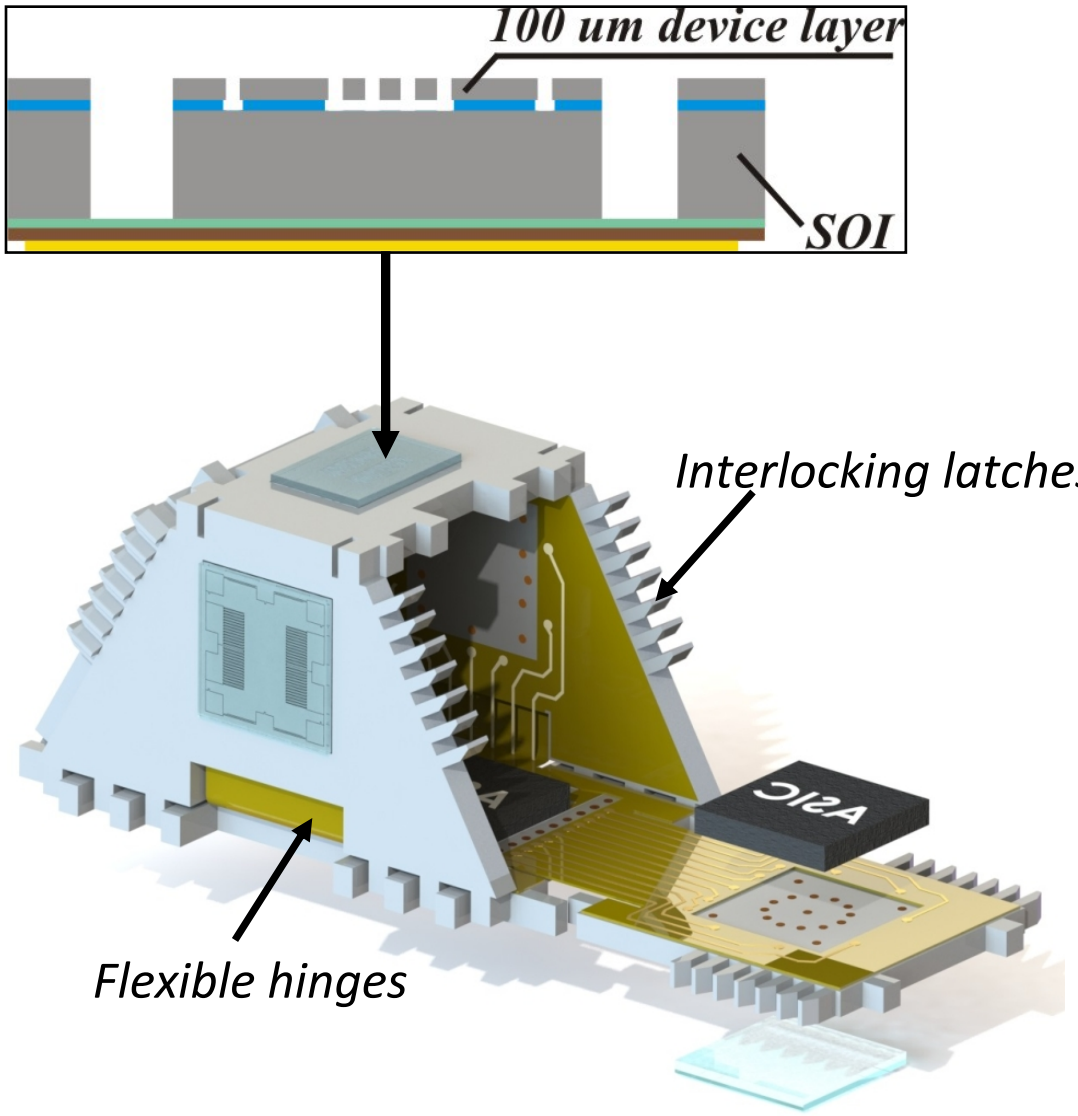
- \+ Reduced footprint
- \- Bonding process Vacuum packaging

Single-chip



- \+ Small volume
- \- Compromised performance of in & out-of-plane devices

Silicon Origami-like TIMU

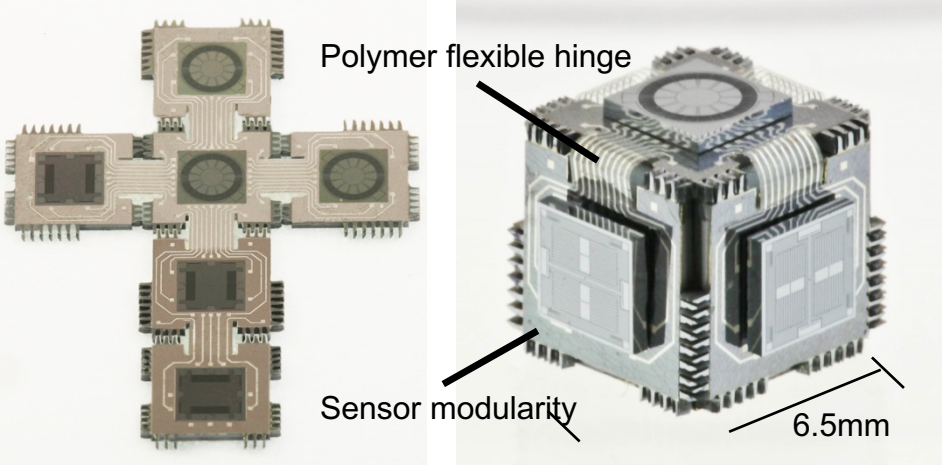


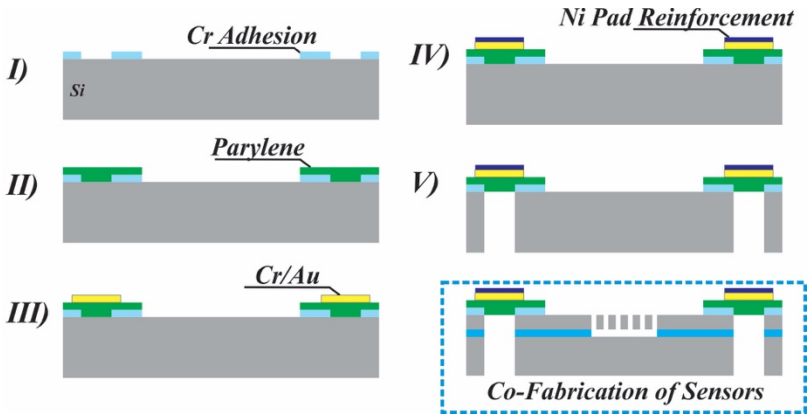
1. Batch fabrication

2. Small volume

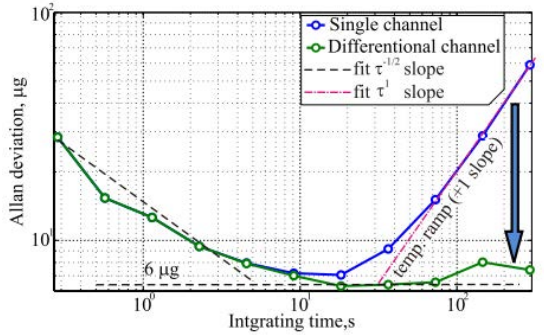
3. High Sensitivity
High aspect ratio single-axis sensors

Current Results:
Silicon Origami-Like TIMU



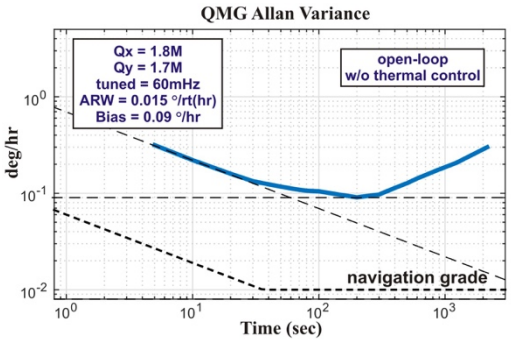


Accelerometer



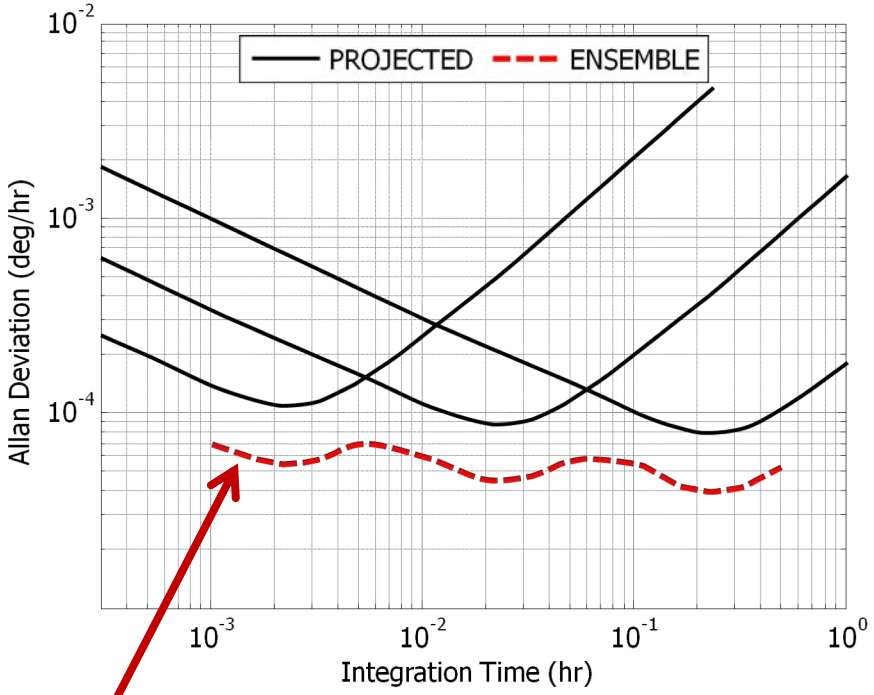
Zotov, Sergei A., et al. "High quality factor resonant MEMS accelerometer with continuous thermal compensation." *IEEE Sensors Journal* 15.9 (2015): 5045-5052.

Gyroscpe

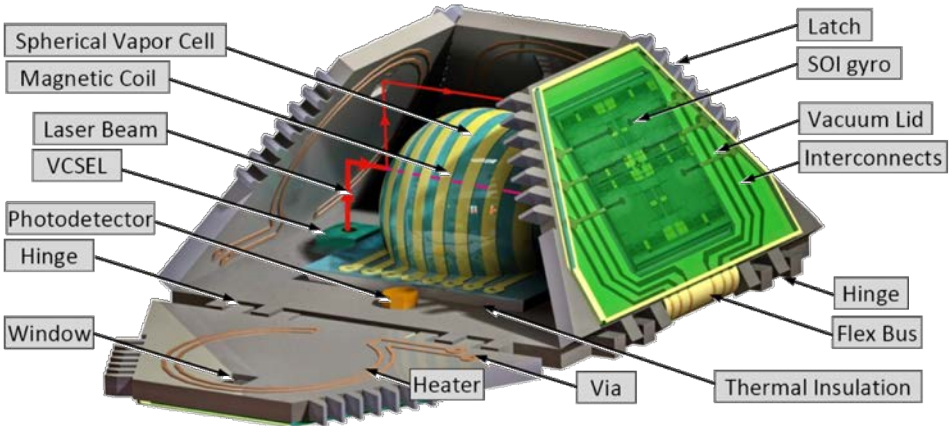


Askari, S., Asadian, M., Kakavand, K., and Shkel, AM. "Near-Navigation Grade Quad Mass Gyroscope with Q-factor Limited by Thermo-Elastic Damping", Hilton Head 2016

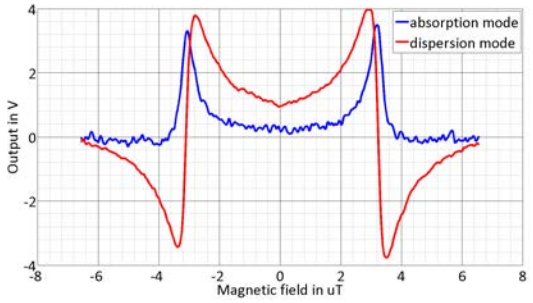
Combinatorial approach



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

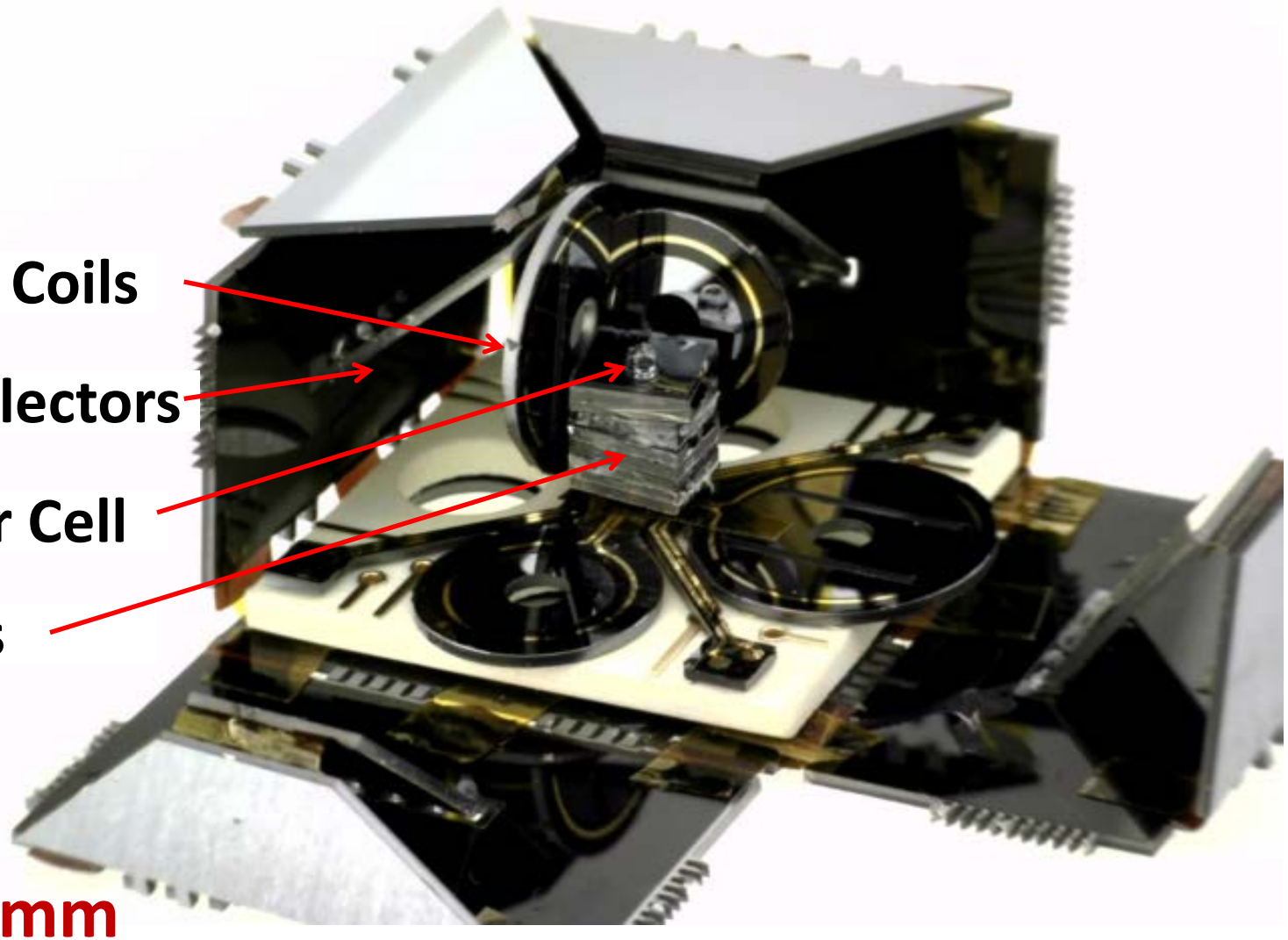


Andrei M. Shkel, "The Chip-Scale Combinatorial Atomic Navigator", GPS World, August 2013.



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

Atomic microsystems



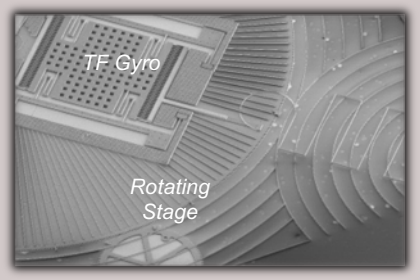
20x20x12mm

Path to the Future

Precision fabrication & new materials

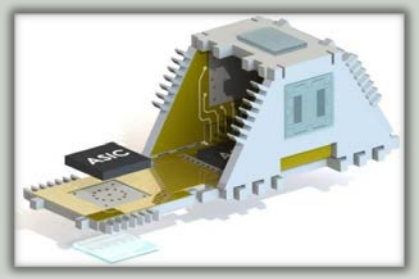
3D wineglass structure, UC Irvine

In-situ calibration



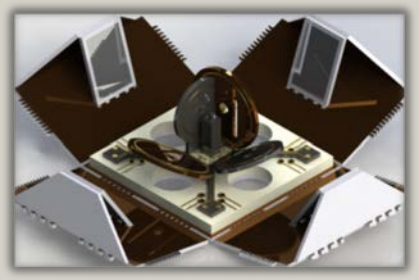
Calibration Stage
Sandia Nat. Labs/Draper Lab

Novel assembly techniques



Folded IMU, UC Irvine

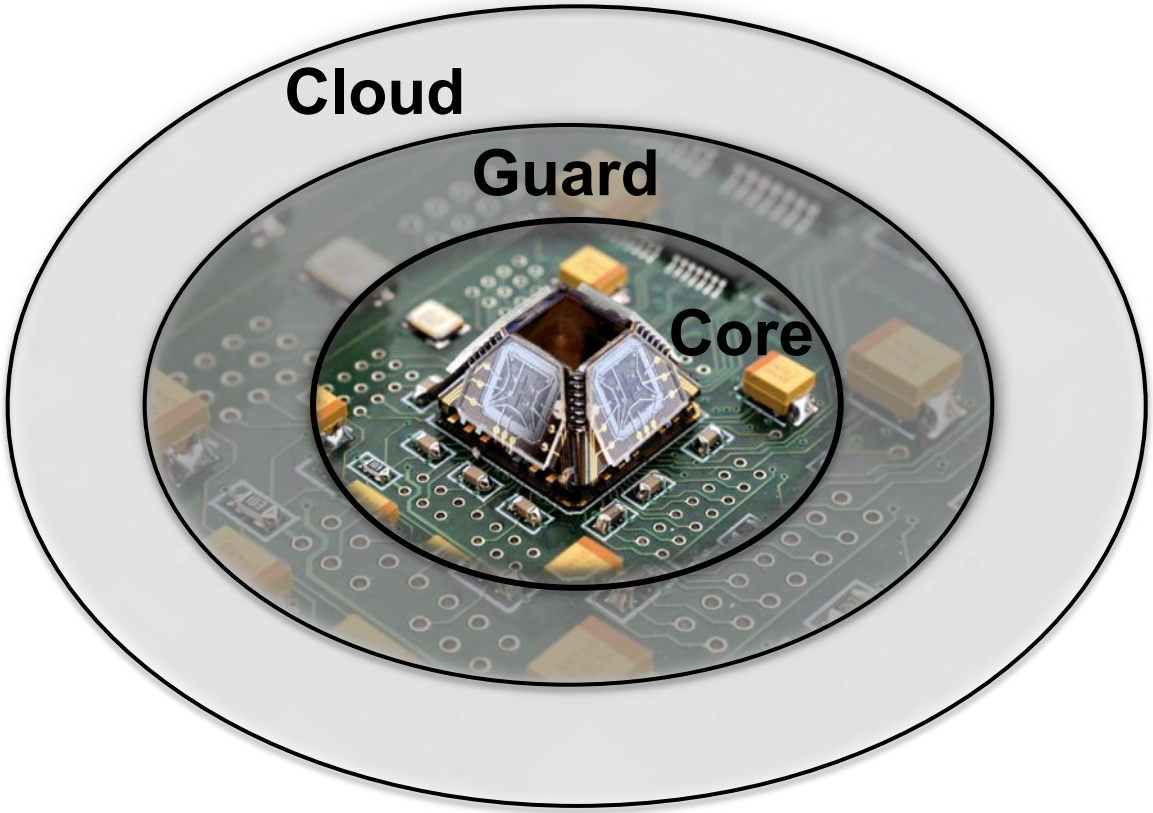
Atomic accuracy



NMR IMU, UC Irvine

If I were to guess …

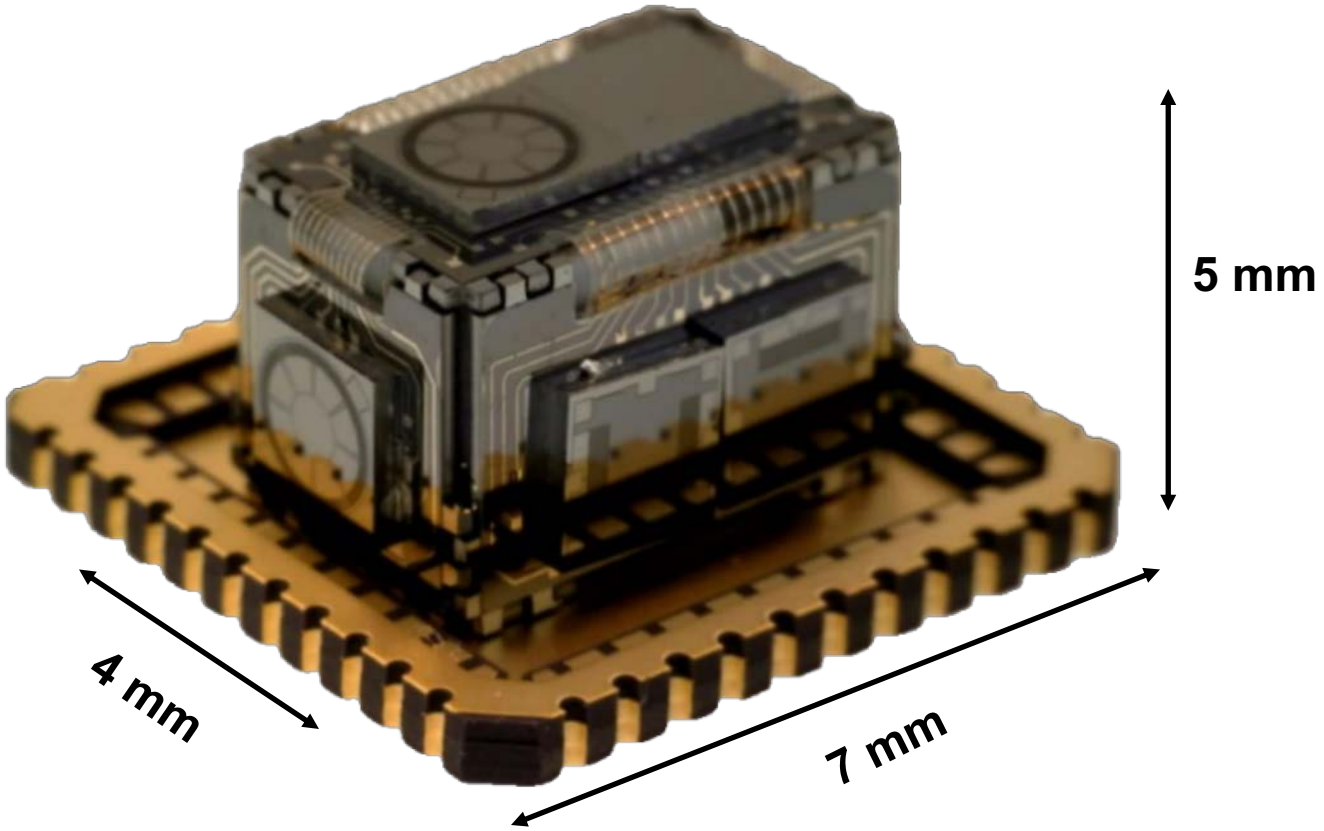
Ultimate Navigation Chip (uNavChip)



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

Provide maximum autonomy, security, precision

Phase I prototype (NIST PSIAP-LBS)

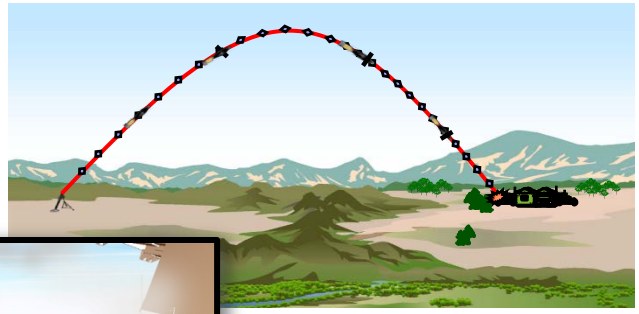


- This work was performed under the financial assistance award: 70NANB17H192 from U.S. Department of Commerce, National Institute of Standards and Technology (NIST). Program Manager: Jeb Benson

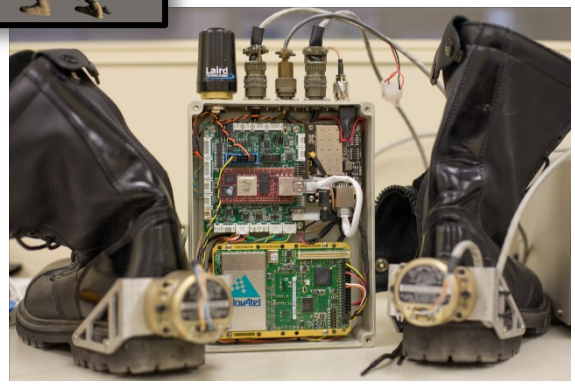
Enabled by precision

Military

Self-contained navigation



Far-Target detection
North-finder



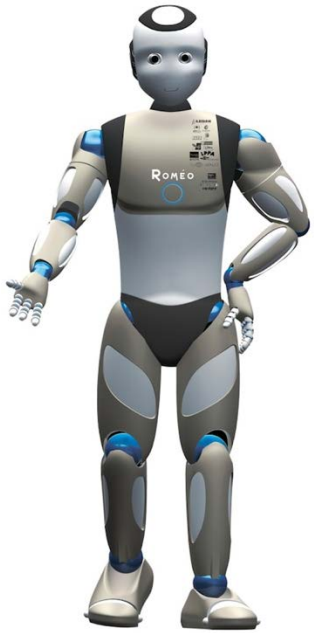
Navigation of dismounts

Consumer & Industrial

- Geolocation
- Stabilization
- Precision timing

Anti-spoofing

Encryption



Stabilization

Acknowledgement

- **DARPA** (current PM: Ron Polcawich, former PM: Robert Lutwak)
  - Micromachined Rate Integration Gyroscopes (**MRIG**)
  - Primary and Secondary Calibration on Active Layer (**PASCAL**)
  - Timing and Inertial Navigation Unit (**TIMU**)
  - Chip-Scale Combinatorial Atomic Navigator (**CSCAN**)
  - Precise Robust Inertial Guidance for Munitions: Advanced Inertial Micro Sensors (**PRIGM: AIMS**)
- **NIST** (PM: Jeb Benson)
  - Ultimate Navigation Chip utilizing deterministic probabilistic and signals of opportunity **(NIST: uNavChip)**

Research *consumes $ to create ideas,*
Innovation *consumes ideas to create $*

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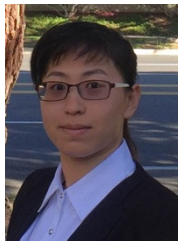
(publications, IP, projects)





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