Precision Navigation, Timing, and Targeting enabled by Microtechnology: Are We there yet?

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“White space” in guidance and navigation

70% of missile missions have durations less than 3 minutes*

* Based on findings from budget documents for procurement programs (P-1) from the Office of the Under Secretary of Defense Comptroller Information System database for Army, Navy, and Air Force procurement for 2009, 2010 and 2011. Any platforms where there was no data in P-1 budgetary documents were assumed to be zero.

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The goal of the MicroPNT program is to achieve self-contained (GPS-independent) inertial navigation and timing, operable under severe dynamic environments through the integration of self-calibrating sensors in a micro-scale package.

The program addresses emerging DOD needs to:

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SOA*</th>
<th>MicroPNT Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>65,000 mm³</td>
<td>8 mm³</td>
</tr>
<tr>
<td>Gyro bias</td>
<td>4 deg/hr</td>
<td>0.01 deg/hr</td>
</tr>
<tr>
<td>Accelerometer bias</td>
<td>4 mg</td>
<td>0.1 mg</td>
</tr>
<tr>
<td>Short-term time loss</td>
<td>100 ns/min</td>
<td>1 ns/min</td>
</tr>
<tr>
<td>Long-term time loss</td>
<td>160 ns/month</td>
<td>32 ns/month</td>
</tr>
<tr>
<td>Power level</td>
<td>5 W</td>
<td>~1 W</td>
</tr>
</tbody>
</table>

* Best properties from multiple technologies:
  - MEMS IMU
  - Quartz Oscillators
  - Magneto Optical Trap

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**MicroPNT scope:**
C-SCAN, PALADIN, PASCAL, TIMU, MRIG, IMPACT, IT-MARS, MINT, NGIMG, CSAC

- **“New Physics” at micro-scale:**
  - Inertia of elastic waves
  - Atomic transitions
  - Magnetically levitated solids
  - Cold atom interferometry
  - Hot atom interferometry

- **Algorithms for compensation of bias and scale-factor drift:**
  - Combinatorial systems of inertial sensors using dissimilar physics
  - Integrated self-calibration on-chip to improve long-term bias and scale factor stability
  - Zero-velocity updating algorithms to compensate for in-run bias and scale factor drift

- **Innovative microfabrication:**
  - New materials (CVD diamond, quartz, BMGs, fused silica, ULE glass)
  - 3D structures (toroids, spheres, wineglass)
  - Precision (tolerances of 10^-4 to 10^-6)
  - Wafer-level batch fabrication to reduce SWAP and cost

- **Technology transition:**
  - Early engagement of DoD branches in DARPA/MTO programs
  - Ruggedization to increase TRL
  - Independent gov’t evaluation as early as Phase II to increase user buy-in

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“New physics” on the micro-scale

**Atomic Transitions and Laser Cooling**

- Frequency determined by an atomic transition energy
- $^{133}\text{Cs}$
- $\nu = \frac{\Delta E}{\hbar} = 9\,192\,631\,770\,\text{Hz}$
- Precise Number of Energy Transitions

**Larmor Precession**

- $\omega_{\text{Al}} = \gamma_{\text{Al}} (B_0 + B_{\text{Xe}})$
- $B_0 + B_{\text{Xe}} \rightarrow \omega_{\text{Xe}} = \gamma_{\text{Xe}} B_0$

**Vibratory Gyroscopes**

- Vibratory mass on elastic support
- Inertia of Elastic Waves in Solids

$$\begin{align*}
|y(t)| &= \frac{2X_D \Omega Q}{\omega_n} \\
\phi &\approx -2 \frac{\Omega Q}{\omega_n} \\
\phi &= -\int \Omega \, dt
\end{align*}$$

**Electrostatic Levitation**

$$\begin{align*}
I_T \alpha_x - (I_T - I_P) \Omega \omega_y &= \Sigma M_{X,1} \\
I_T \alpha_y - (I_P - I_T) \Omega \omega_x &= \Sigma M_{Y,1}
\end{align*}$$

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Self-calibration on-a-chip

Motivation
- Bias Drift (illustration)
- Output (Voltage)
- Input (Rotation)
- Ideal response
- Drifted response

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

Approach
- Gyroscope
- Calibration Stage

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. Co-fabricate
   1. Fabricate sensor directly on calibration stage
2. Excite
   2. Periodically apply reference stimulus (e.g. oscillatory)
3. Extract
   3. Extract reference stimulus and sensor response
4. Reset
   4. Recover new I/O relationship and reset bias

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“White space” in guidance and navigation

70% of missile missions have durations less than 3 minutes*

Current micro-PNT efforts

Ballistic

Precision Engagement with GPS-assisted guidance

Speed of Platform (km/hr)

Range of Mission (km)

- M-16
- Grenade Launcher
- Missile 1
- Missile 2
- Missile 3
- Missile 4
- Missile 5
- Missile 6
- Missile 7
- Missile 8
- Missile 9
- HMMWV
- Micro UAV
- SEALs Walking in Cave
- Soldier Walking in Open Field
- Soldier Walking in Cave

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Approved for Public Release, Distribution Unlimited
“White space” in guidance and navigation

98% of missile missions have durations less than 18 minutes*

Current micro-PNT efforts

C-SCAN effort

Ballistic

Precision Engagement with GPS-assisted guidance

Range of Mission (km)

1,000

100

10

1

10 sec

3 min

1 hr

24 hr

Speed of Platform (km/hr)

10,000

100

10

1

* Based on findings from budget documents for procurement programs (P-1) from the Office of the Under Secretary of Defense Comptroller Information System database for Army, Navy, and Air Force procurement for 2009, 2010 and 2011. Any platforms where there was no data in P-1 budgetary documents were assumed to be zero.

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Chip-Scale Combinatorial Atomic Navigator (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

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Example simulation of three types of gyros

- Utilize ensemble of gyros to widen the range of averaging intervals
- Combinatorics anticipate simultaneous improvement in start-up time, bias/scale-factor stability, dynamic range, sensitivity, and angle random walk

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

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Micro Rate Integrating Gyroscopes (MRIG)

- Potential for decrease in cost from $1,000 to $100 per gyro axis.
- Near navigation-grade gyro performance in form factor smaller than today’s tactical grade gyros.

To eliminate wear-out, exploit inertial properties of elastic standing waves in solids. This leverages inherent isotropic behavior in exotic materials.

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Recent Results (MRIG)

- The microPNT program seeks to develop high dynamic range sensors to directly measure the angle of rotation.
- The program explores new processes and high-Q materials for fabricating micro-scale 3D structures.
- This effort is currently in Phase II of a three phase development.

<table>
<thead>
<tr>
<th>Structures</th>
<th>UC, Berkeley</th>
<th>Honeywell</th>
<th>Cornell</th>
<th>Univ. of Michigan</th>
<th>Northrop Grumman</th>
<th>Yale</th>
<th>Draper</th>
<th>UC, Irvine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>CVD Diamond</td>
<td>ULE Glass / CVD Diamond</td>
<td>Silicon Nitride</td>
<td>Fused Silica</td>
<td>SiO₂</td>
<td>Bulk Metallic Glass</td>
<td>CVD Diamond</td>
<td>Pyrex, ULE Glass, Quartz</td>
</tr>
<tr>
<td>Frequency mismatch (Hz)</td>
<td>5</td>
<td>13</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>20</td>
<td>240</td>
<td>0.15</td>
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<tr>
<td>Ring down time (sec)</td>
<td>0.11</td>
<td>0.8</td>
<td>0.16</td>
<td>8.3</td>
<td>0.28</td>
<td>1.5</td>
<td>0.23</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Program objective is 1 Hz frequency mismatch and 100 sec ring down time.
## Micro-PNT objective

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

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

**Commercialized Product**
- **CSAC**
  - ~$1500, 20 mW, 6 cm³, 35 gram
  - <1 µs time loss after 1 week while exposed to MIL-STD

**Graduating from DARPA**
- **MI NT** Velocity assisted micro-IMU
  - 20 mW, 5 cm³, near Nav-grade
  - 16m accuracy after 4hr GPS-denied environment (gov’t tested)
- **NGI MG** NMR Gyro
  - 20 mW, 5 cm³, near Nav-grade

**Infancy**
- **MRI G**
- **IMPACT**
- **TIMU**
- **PASCAL**
- **C-SCAN**
  - New Physics
  - Algorithms
  - Microfab
  - Technology integration

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Precision engagement

10 m (or better) CEP from hundreds of miles

- Define fast the intended target (in seconds)
- Know your initial conditions
- GN&C without external signals

All need to be done in the same coordinate system

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