Emerging Microsystem Technologies for Autonomous Positioning, Navigation, and Timing (PNT)

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Program Manager, Microsystems Technology Office (MTO)

National Space-Based PNT Advisory Board

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DARPA PNT Objectives

- Achieve GPS-level performance under all application scenarios
  - Eliminate GPS as single point of failure
  - Provide redundant capabilities and architectures with no single point of failure
  - Provide optimal solution based on all available data sources

- Outperform GPS for disruptive capabilities
  - Tactical time distribution, advanced communications, and EW
  - Long-term PNT in environments where GPS was never designed for use: undersea, underground, indoors
  - High-precision relative PNT for cooperative effects (multi-static radar, distributed SIGINT, autonomous formation flying, time transfer)
Position is Time is Position

Speed of Light = 1 foot / 1 nanosecond

Coordinated engagement

Coherent EW

Bistatic RADAR

http://woof.tistory.com/217
http://code7700.com/gps.html
State-of-the-Art Clocks

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.
DARPA Clock Investment Strategy

MEMS Performance

Time to 1 µs Error [s]

CSWaP [$\cdot m^3\cdot kg\cdot W$]

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### Timing Error

\[
\Phi(\tau) = \Phi_0 + f_0 \times \tau + \frac{1}{2} f_0' \times \tau^2 + \frac{\sigma_y(\tau)}{\sqrt{3}} \times \tau + \int_0^\tau f[T(t)] \, dt + \int_0^\tau f[B(t)] \, dt + \ldots
\]

- **Initial time error (sync)**
- **Initial freq. error (cal)**
- **Noise-driven wander (Instability)**
- **Frequency Sensitivity to Temperature (TempCo)**
- **Frequency Sensitivity to Magnetic Field**

### CSAC Typical application model (\(\Delta T=10^\circ C\))

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Timing error, (\Phi), after 6-hour calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\tau=1) hour</td>
</tr>
<tr>
<td>Initial Sync</td>
<td>(\Phi_0)</td>
</tr>
<tr>
<td>Initial Cal</td>
<td>(f_0)</td>
</tr>
<tr>
<td>Frequency Aging</td>
<td>(f'_0)</td>
</tr>
<tr>
<td>Instability</td>
<td>(\sigma_y)</td>
</tr>
<tr>
<td>TempCo</td>
<td>(f[T])</td>
</tr>
</tbody>
</table>

**Total:**

| 360 ns | 8.7 \(\mu\)s | 65 \(\mu\)s | 436 \(\mu\)s | 436 \(\mu\)s |

**Total accumulated time error**

\[
\Phi_0 + f_0 \times \tau + \frac{1}{2} f_0' \times \tau^2 + \frac{\sigma_y(\tau)}{\sqrt{3}} \times \tau + \int_0^\tau f[T(t)] \, dt + \int_0^\tau f[B(t)] \, dt + \ldots
\]
Miniature Atomic Clocks

• **Chip-Scale Atomic Clock (CSAC) program:**
  - 100 mW, 15 cm³, 1 µs/1 day
  - Fully transitioned to industrial production (> 30,000 units shipped)
  - Second-source development underway by U.S. Army ManTech program

• **Integrated Micro-Primary Atomic Clock Technology (IMPACT) program:**
  - Objective: CSAC size with rackmount cesium-beam performance (32 ns/1 month)
Limitations of Gas Cell Atomic Oscillators

TempCo and Drift have the same root causes:
  • Pressure and composition of cell contents ("buffer gas shift")
  • Laser spectrum ("light shift")

Superior performance requires:
  • Atoms in vacuum
  • Light off during interrogation

Possible ACES interrogation architectures:
  • Laser-cooled/trapped neutral atoms
  • Trapped ions
  • Interrogation of optical transitions
  • Other?
ACES Program Goals

ACES: Battery powered clock with near-cesium beam performance

\[ \Delta T = 10 \, ^\circ C \]

Time to 1 \( \mu \)s Error [s]

CSWaP [\$ \cdot m^3 \cdot kg \cdot W]
## ACES TA-1 Program Milestones

### TA-1 over three Phases:

<table>
<thead>
<tr>
<th></th>
<th>Proof-of-concept</th>
<th>Integrated Physics</th>
<th>Deliverable Clock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
<td>Phase 3</td>
</tr>
<tr>
<td>Aging</td>
<td>N/A</td>
<td>&lt; $10^{-12}$/month</td>
<td>&lt; $10^{-13}$/month</td>
</tr>
<tr>
<td>TempCo (-40°C to +85°C)</td>
<td>N/A</td>
<td>&lt; $10^{-14}$/°C</td>
<td>&lt; $10^{-15}$/°C</td>
</tr>
<tr>
<td>ReTrace (on/off/on, 4/24/4 hours)</td>
<td>$\Delta y &lt; 10^{-11}$</td>
<td>$\Delta y &lt; 10^{-12}$</td>
<td>$\Delta y &lt; 10^{-13}$</td>
</tr>
<tr>
<td>Volume</td>
<td>N/A</td>
<td>30 cm$^3$</td>
<td>50 cm$^3$</td>
</tr>
<tr>
<td>Power</td>
<td>250 mW</td>
<td>250 mW</td>
<td>250 mW</td>
</tr>
<tr>
<td>Instability</td>
<td>$\sigma_y(\tau) &lt; 1 \times 10^{-11} / \tau^{1/2}$</td>
<td>$\sigma_y(\tau) &lt; 1 \times 10^{-11} / \tau^{1/2}$</td>
<td>$\sigma_y(\tau) &lt; 1 \times 10^{-11} / \tau^{1/2}$</td>
</tr>
<tr>
<td>Notes</td>
<td>Power applies to physics package, which includes all vacuum, optical, and thermal control components</td>
<td>Size and power apply to physics package only, which includes all vacuum, optical, and thermal control components</td>
<td>Size and power apply to fully packaged device, which includes all physics and electronic components</td>
</tr>
</tbody>
</table>

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Simplified Missile/Munition Profiles

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Munitions Navigation

**Navigation System**

- **GPS**
  - Algorithms
  - Output: \( x, y, z, v_x, v_y, v_z \)

**Inertial Navigation System (INS)**

- **Clock**
- **IMU**
  - **Output:** \( x, y, z, v_x, v_y, v_z \)

**Inertial Measurement Unit (IMU)**

- **Gyro**
- **Accel**
  - Sensor Control & Readout
  - **Output:** \( a_x, a_y, a_z, \alpha, \beta, \gamma \)

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Source: defense-update.com

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State-of-the-Art Accelerometers

MEMS accelerometers are good enough (for now)

\[(x, y, z) \propto \int \alpha \, dt^2 \propto T^2\]
State-of-the-Art Gyroscopes

\[ (x, y, z) \propto \int g \left[ \int \Omega dt \right] dt^2 \propto T^3 \]

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Micro-Scale Rate-Integrating Gyroscope (MRIG)

MRIG Objective:
Micro-scale, high-performance, rate-integrating gyroscope for high-bandwidth high-accuracy inertial navigation

Key Challenges:
Fabrication of high-Q, high-symmetry MEMS devices

Northrop Grumman
Hemispherical Resonator Gyroscope (HRG)
4W, 250 cm³, $100K

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**TIMU Objective:**
Fully-integrated co-fabricated 6-DOF IMU with extremely low CSWaP

**Key challenges:**
Co-fabrication of high-performance MEMS inertial sensors
Encapsulation requirements for gyros vs. accels
Top-level yield

**TIMU Approaches**

<table>
<thead>
<tr>
<th>Approach</th>
<th>Goal</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic (single die)</td>
<td>Volume [mm³]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Multi-layer (stacked die)</td>
<td>IMU accuracy [CEP, nmi/hour]</td>
<td>Oper.</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Three-dimensional (folded/co-integrated)</td>
<td>Timing accuracy [ns/min]</td>
<td>Oper.</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Power [mW] (-55°C to +85°C)</td>
<td>-</td>
<td>500</td>
<td>200</td>
</tr>
</tbody>
</table>
Primary and Secondary Calibration on Active Layer

PASCAL Objective:
Realize MEMS inertial sensors with on-chip calibration
Absolute calibration is essential for north-finding

Key challenges:
Co-fabrication of high-performance MEMS devices and calibration stages
Calibrator calibration, numerous moving parts
“True” reversibility

Technical Area 1 (TA1): Mechanical self-calibration
- Co-integrated gyroscope + rotary stage
- External physical stimulus
- Maytagging, dithering
- Fabrication challenges delayed TA1 performer transition to Phase 3; results anticipated in Spring 2016

Technical Area 2 (TA2): Electronic self-calibration
- Electronic stimulus mimics rotation
- Mode-reversal, virtual carouseling
- Four performers (TA2) have submitted devices for Phase 2 government evaluation

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© Georgia Tech
SOA Gyroscopes

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Precise Robust Inertial Guidance for Munitions (PRIGM)

Navigation-Grade Inertial Measurement Unit (PRIGM:NGIMU)

GPS-free navigation of glide munitions for 180 sec

Smaller & Better

CSWaP [$\cdot m^3\cdot kg\cdot W$]

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**Motivation**
- Enable guided munitions in GPS-contested theaters by 2020

**Objective**
- Eliminate compromise between low-CSWaP, tactical-grade MEMS and high-CSWaP, navigation-grade RLG/iFOG-based IMUs
- 6.3 program will deliver 10 prototype drop-in replacement navigation-grade MEMS IMUs in 2019
- Engage Service Labs to perform flight demos in 2020

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**Navigation-grade performance with MEMS CSWaP**

<table>
<thead>
<tr>
<th>Current IMU Technology</th>
<th>PRIGM:NGIMU Enabled Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nav-Grade IMU</td>
<td>Navigation-Grade IMU</td>
</tr>
<tr>
<td>Ring laser gyros, quartz accels</td>
<td>SOA MEMS gyros &amp; accels</td>
</tr>
<tr>
<td><img src="image1.png" alt="Nav-Grade IMU" /></td>
<td><img src="image2.png" alt="Navigation-Grade IMU" /></td>
</tr>
<tr>
<td><img src="image3.png" alt="Tactical-Grade IMU" /></td>
<td><img src="image4.png" alt="SOA MEMS gyros &amp; accels" /></td>
</tr>
<tr>
<td><img src="image5.png" alt="MEMS gyros &amp; accels" /></td>
<td></td>
</tr>
<tr>
<td><img src="image6.png" alt="Ring laser gyros, quartz accels" /></td>
<td><img src="image4.png" alt="SOA MEMS gyros &amp; accels" /></td>
</tr>
</tbody>
</table>

© Honeywell
**PRIGM:NGIMU Program Objectives**

**Program Deliverables:** 10 MEMS-based IMUs at TRL 6 that are DoD-standard, tactical-grade drop-in replacements with navigation-grade performance

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>Objective</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>82</td>
<td>cm³</td>
</tr>
<tr>
<td>Weight</td>
<td>160</td>
<td>g</td>
</tr>
<tr>
<td>Power</td>
<td>&lt; 3</td>
<td>W</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-54 to +85</td>
<td>°C</td>
</tr>
<tr>
<td>Vibration DC to 2 kHz</td>
<td>7.7</td>
<td>gRMS</td>
</tr>
<tr>
<td>Shock survivability</td>
<td>20,000</td>
<td>g</td>
</tr>
<tr>
<td>Bandwidth (min. @ -90° phase lag)</td>
<td>70</td>
<td>Hz</td>
</tr>
</tbody>
</table>

**Gyroscope**

| Operating range                 | ± 900     | °/sec   |
| Turn-on to turn-on bias repeatability | 0.01   | °/hr, 1σ |
| Scale factor repeatability      | 5         | ppm     |

**Accelerometer**

| Operating range                 | ± 60      | g       |
| Turn-on to turn-on bias repeatability | 25    | µg, 1σ  |
| Scale factor repeatability      | 25        | ppm     |
Stability Specification (Allan Deviation)

<table>
<thead>
<tr>
<th>( \tau ) [sec]</th>
<th>Gyroscope ( \sigma_\Omega(\tau) ) ( ^\circ/\text{hr} )</th>
<th>Accelerometer ( \sigma_a(\tau) ) [mg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.66</td>
<td>0.19</td>
</tr>
<tr>
<td>1</td>
<td>0.21</td>
<td>0.06</td>
</tr>
<tr>
<td>10</td>
<td>0.066</td>
<td>0.01</td>
</tr>
<tr>
<td>100</td>
<td>0.021</td>
<td>0.01</td>
</tr>
<tr>
<td>1000</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

ARW = 0.0035 \( ^\circ/\text{hr}^{1/2} \)

VRW = 10 mm/sec/hr\(^{1/2} \)

Flicker Floor = 0.01 \( ^\circ/\text{hr} \)

Flicker Floor = 0.01 mg
SOA Gyros: Path to Advanced Inertial Micro Sensors

Advanced Inertial Micro Sensors (PRIGM: AIMS)

TA-1: Navigate THROUGH gun launch
TA-2: GPS-free navigation for 18 minutes

Smaller & Better

Time to 10 m CEP Error [s]

CSWaP [$\cdot m^3\cdot kg\cdot W$]

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AIMS Approaches: Rate Integrating Gyroscopes

Advantages:
- No mechanical bandwidth limit
- No integration error
- Certain candidate geometries (disks, shells) are shock and vibration tolerant
- Silicon carbide (SiC) provides environmental robustness

Challenges:
- High symmetry required to achieve high-performance
- Poor SNR due to circumferential sensing

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AIMS Approaches: Photonic Gyroscopes

Waveguide Optical Gyroscopes: Integrated FOG/RLG on a chip

Advantages:
- No moving parts
- Tight integration reduces CSWaP and key environmental sensitivities of conventional FOG/RLG

Challenges:
- Low-loss waveguides
- Vertical integration of multiple waveguides for higher sensitivity
- High SNR needed to overcome smaller enclosed area than fiber spool
- Photonic integration

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Optically Sensed MEMS Accelerometers

Optical rather than capacitive sensing of MEMS position for high SNR

Advantages:
- High displacement sensitivity allows for stiffer structures (gun-hardened)
- Stiffer structures → higher bandwidth
- Potential for self-calibration in units of laser wavelength ("light as a ruler")

Challenges:
- Opto-electronic-MEMS co-fabrication/integration
- Laser wavelength stability
**AIMS Approaches: Acoustic Gyros, Accelerometers**

**Surface Acoustic Wave (SAW) Gyroscopes**

**Resonant and Thermal Accelerometers**

**Advantages:**
- No moving parts (environmental robustness, gun-hardened)
- Increased gyro sensitivity due to optical readout

**Challenges:**
- Thermal stability

**DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.**
SOA Gyros: Path to Advanced Inertial Micro Sensors

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.
<table>
<thead>
<tr>
<th>SWaP &amp; Survival Metric</th>
<th>TA1</th>
<th>TA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>1 cm³</td>
<td>1 cm³</td>
</tr>
<tr>
<td>Weight</td>
<td>1 g</td>
<td>1 g</td>
</tr>
<tr>
<td>Power</td>
<td>250 mW</td>
<td>250 mW</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-54 to +85 °C</td>
<td>-54 to +85 °C</td>
</tr>
<tr>
<td>Vibration (5Hz to 5kHz)</td>
<td>50 g&lt;sub&gt;RMS&lt;/sub&gt;</td>
<td>7.7 g&lt;sub&gt;RMS&lt;/sub&gt;</td>
</tr>
<tr>
<td>Shock survivability</td>
<td>50,000 g</td>
<td>20,000 g</td>
</tr>
</tbody>
</table>

### Operating Conditions

<table>
<thead>
<tr>
<th></th>
<th>Gyroscope</th>
<th>Accelerometer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TA1</td>
<td>TA2</td>
</tr>
<tr>
<td>Full-Scale Range</td>
<td>±100,000 °/s</td>
<td>±900 °/s</td>
</tr>
<tr>
<td>Bias Repeatability</td>
<td>0.01 °/hr</td>
<td>0.001 °/hr</td>
</tr>
<tr>
<td>Bias Environmental Sensitivity</td>
<td>0.01 °/hr</td>
<td>2e-5 °/hr</td>
</tr>
<tr>
<td>Scale Factor Repeatability</td>
<td>1 ppm</td>
<td>0.01 ppm</td>
</tr>
<tr>
<td>Scale Factor Environmental Sensitivity</td>
<td>1 ppm</td>
<td>1 ppm</td>
</tr>
</tbody>
</table>
### PRIGM: AIMS Program Objectives

#### Stability Specification (Allan Deviation)

<table>
<thead>
<tr>
<th>( \tau ) [sec]</th>
<th>Gyroscope ( \sigma_\Omega(\tau) ) [°/hr]</th>
<th>Accelerometer ( \sigma_a(\tau) ) [mg]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TA1</td>
<td>TA2</td>
</tr>
<tr>
<td>0.1</td>
<td>0.66 2e-3</td>
<td>0.19 1.9e-2</td>
</tr>
<tr>
<td>1</td>
<td>0.21 6e-4</td>
<td>0.06 6e-3</td>
</tr>
<tr>
<td>10</td>
<td>0.066 2e-4</td>
<td>0.01 1.9e-4</td>
</tr>
<tr>
<td>100</td>
<td>0.021 6e-5</td>
<td>0.01 1e-4</td>
</tr>
<tr>
<td>1000</td>
<td>0.01 2.5e-5</td>
<td>0.01 1e-4</td>
</tr>
</tbody>
</table>

**Flicker Floor**
- Gyroscope: \( 2.5e^{-5} \) °/hr
- Accelerometer: \( 1e^{-4} \) mg
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