Micro-Technology for Positioning, Navigation, and Timing
Towards PNT Everywhere and Always

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Program Manager
Microsystems Technology Office
Defense Advanced Research Projects Agency

Stanford PNT Symposium
Stanford, CA
October 29, 2014

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Formed in 1958 to **PREVENT** and **CREATE** strategic surprise.

Capabilities, mission focused
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Finite duration projects
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Diverse performers
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Multi-disciplinary approach...from basic research to system engineering

We focus on high risk, high reward R&D for national security.
DARPA Technical Offices

BTO
- Biology, Technology & Complexity
- Restore and Maintain Warfighter Abilities
- Harness Biological Systems
- Apply Biological Complexity at Scale

DSO
- Discover, Model, Design & Build
- Physical Sciences
- Mathematics Materials and Manufacturing
- Autonomy
- Science of Complexity

I2O
- Information, Innovation & Cyber
- Cyber
- Data Analysis at Massive Scales
- ISR Exploitation

MTO
- Electronics, Photonics & MEMS
- Biological Platforms
- Computing
- Electronic Warfare
- Manufacturing
- Novel Concepts
- Photonics
- Positioning, Navigation and Timing
- Thermal Management

STO
- Networks, Cost Leverage & Adaptability
- Battle Mgmt, Command & Control
- Comms & Networks
- Electronic Warfare
- Positioning, Navigation and Timing

TTO
- Weapons, Platforms & Space
- Air Systems
- Ground Systems
- Marine Systems
- Space Systems

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DARPA PNT programs focused on reducing GPS reliance

Achieve GPS-level timing and positioning performance without GPS
  • Eliminate GPS as single point of failure
  • Provide redundant capabilities and adaptable architectures
  • Provide optimal PNT solution based on all available data sources

Outperform GPS for disruptive capabilities
  • Ultra-stable clocks (short and long term) for electronic warfare, ISR, and communications
  • Persistent PNT in environments where GPS was never designed for use: undersea, underground, indoors
  • High precision PNT for cooperative effects (distributed electronic warfare, distributed ISR, autonomous formation flying, time transfer to disadvantaged users)
Notional all source navigation

- C-band comm.
- GPS
- IMU
- Ku-band comm.
- alimeter
- air speed
- nose camera
- SAR imagery
- EO/IR imagery
- SIGINT (not shown)

current navigation sensors
existing sensors applicable to all source navigation
Adaptable Navigation Sensors and Systems

Global Navigation Satellite Systems
- Present: GPS, GLONASS, WAAS, EGNOS
- Future: Galileo, BeiDou, QZSS, IRNSS

Inertial Sensors
- Present: iFOG, RLG, MEMS
- Future: PINS-HiDRA, TIMU, C-SCAN, MRIG, PASCAL

Clocks
- Present: Cesium beam, Rubidium and quartz oscillators, CSAC
- Future: QuASAR, IMPACT, MEMs

Signals of Opportunity
- Future: Cell towers, SATCOM, Radio, TV, Lightning, etc.

Other Sensors
- Present: Camera, pitot, altimeter, RADAR, magnetometer, etc.

Optimal solution algorithms
Plug-and-play architectures

Distributed and future-proof
Program Objective:

*Every thing knows where and when it is all of the time*

*“PNT Everywhere”*

- Specifically: Unaided navigation and timing error of 20 m and 1 \( \mu \)s at 1 hour
- Applications have requirements on Cost, Size, Weight, and Power (CSWaP)
- At present, we can meet performance requirements in an unmoving laboratory, with unlimited power, for about $1M.
- DARPA micro-PNT goal: 10 mm\(^3\), 2g, 1W
- Where are the off-ramps?
  - For many platforms: 30,000 cm\(^3\), 10 kg, 10 W, + $10,000
  - For most platforms: 1000 cm\(^3\), 1 kg, 1W, + $1000.
  - For EVERY platform: 1 cm\(^3\), 100 g, 100 mW, $100


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DoD Munition Profiles

Source: http://en.wikipedia.org/wiki/List_of_active_missiles_of_the_United_States_military

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Battery-powered atomic timing
- Next-gen GPS
- Freq. Agile Radio
- Geolocation
- ISR
- IED defeat
- Remote sensing
- Calibration

DARPA Timing Programs
Gyroscope Technology Gaps

- MEMS Gyroscopes (current micro-PNT efforts: PASCAL, MRIG, TIMU)
  - Super-low CSWaP (< $50, < 1 cm³, < 100 mW)
  - **Gap**: Performance, mostly bandwidth, calibration drift and temperature sensitivity

- Atomic Gyroscopes (current micro-PNT efforts: C-SCAN)
  - Superb stability and accuracy
  - Viable candidate for navigation in FY2030
  - **Gap**: Only lab demonstrations to date; enabling atomic physics components needed

- Optical Gyroscopes (e.g. RLG and iFOG)
  - Good stability and accuracy
  - Candidate technology for gyrocompassing
  - **Gap**: Cost and SWaP ($25K, 500 cm³, 2W); MEMS-based solution?
Primary and Secondary Calibration on Active Layer

**PASCAL Objective:**
Realize MEMS inertial sensors with on-chip calibration to address long-term drift of bias and scale factor

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

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<table>
<thead>
<tr>
<th>PASCAL Metrics</th>
<th>Ph I</th>
<th>Ph II</th>
<th>End Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume [mm³]</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Bias stability (1 month) [ppm]</td>
<td>100</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Scale factor stability (1 month) [ppm]</td>
<td>100</td>
<td>10</td>
<td>1</td>
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## Approaches: Active Layer Stage (TA1)

<table>
<thead>
<tr>
<th>External physical reference stimulus (dithering, maytagging, etc.)</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Diagram 1" /> <img src="image2.png" alt="Diagram 2" /></td>
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<table>
<thead>
<tr>
<th>Honeywell</th>
<th>University of Michigan</th>
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</thead>
<tbody>
<tr>
<td>Dr. Grant Lodden</td>
<td>Prof. Khalil Najafi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sandia National Labs/Draper Laboratory</th>
<th>Cornell University</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Murat Okandan</td>
<td>Prof. Amit Lal</td>
</tr>
</tbody>
</table>
**Approaches: Electronic Self-Calibration (TA2)**

<table>
<thead>
<tr>
<th><strong>Electronic interchange of drive/sense (detect and correct for mechanical change)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>PSU-ARL</td>
</tr>
<tr>
<td>Mr. Terry Roszhart</td>
</tr>
<tr>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>UC Berkeley</td>
</tr>
<tr>
<td>Prof. Bernhard Boser</td>
</tr>
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Sandia/Draper MEMS Gyro + Active Layer Gimbal Rotation
**Single-chip Timing and Inertial Measurement Unit (TIMU)**

**TIMU Objective:**
Fully-integrated co-fabricated 6-axis IMU for extraordinarily low CSWaP

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

<table>
<thead>
<tr>
<th>TIMU Metrics</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume [mm³]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>IMU accuracy [CEP, nmi/hour]</td>
<td>Oper.</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Timing accuracy [ns/min]</td>
<td>Oper.</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Power [mW] (-55°C to +85°C)</td>
<td>-</td>
<td>500</td>
<td>200</td>
</tr>
</tbody>
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# Approaches

<table>
<thead>
<tr>
<th>Multi-layer (stacked die)</th>
<th>Monolithic (single die)</th>
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</thead>
<tbody>
<tr>
<td>Honeywell Dr. Bob Horning</td>
<td>University of Michigan Prof. Khalil Najafi</td>
</tr>
</tbody>
</table>

## Three-Dimensional (folded, co-integrated)

<table>
<thead>
<tr>
<th>Evigia Dr. Navid Yazdi</th>
<th>UC Irvine Prof. Andrei Shkel</th>
</tr>
</thead>
</table>
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

**MRIG Goals**
100 mW, 1 cm³, $50

**Output**
- RIG
- TFG

30 Hz 60 Hz

**Courtesy L. Sorenson, HRL**
## Approach: Surface Tension Processes

<table>
<thead>
<tr>
<th>CVD Diamond</th>
<th>Fused Silica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeywell (Dr. Burgess Johnson)</td>
<td>Univ. of Michigan (Prof. Khalil Najafi)</td>
</tr>
<tr>
<td>![CVD Diamond Image]</td>
<td>![Fused Silica Image]</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Bulk Metallic Glass</th>
<th>ULE Glass</th>
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<tbody>
<tr>
<td>Yale University (Prof. Jan Schroers)</td>
<td>UC Irvine (Prof. Andrei Shkel)</td>
</tr>
<tr>
<td>![Bulk Metallic Glass Image]</td>
<td>![ULE Glass Image]</td>
</tr>
</tbody>
</table>
# Approach: Deposition on a Mold

<table>
<thead>
<tr>
<th>Silicon-Based</th>
<th>Nickel Alloy</th>
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<tbody>
<tr>
<td>Northrop / Ga Tech D. Rozelle, Prof. F. Ayazi</td>
<td>Northrop / Georgia Tech D. Rozelle, Prof. F. Ayazi</td>
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<tr>
<td>Cornell University Prof. Sunil Bhave</td>
<td>GE Global Research Christopher Keimel</td>
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<table>
<thead>
<tr>
<th>CVD Diamond</th>
<th>ULE Glass</th>
<th>ALD Al₂O₃</th>
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<tr>
<td>UC Davis Prof. David Horsley</td>
<td>Draper Laboratory Dr. Jon Bernstein</td>
<td>University of Utah Prof. Carlos Mastrangelo</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CU Boulder Prof. Victor Bright</td>
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</tbody>
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Atomic Gyroscopes

• **Similar to clocks, atoms make fabulous gyroscopes**
  • All atoms are the same
  • No manufacturing variance, minimal calibration drift

• **Chip-Scale Combinatorial Atomic Navigator (C-SCAN) Program**
  • Parallel pursuit of two physics architectures
    • Nuclear Magnetic Resonance Gyroscopes (NMRG)
      • Each atom is a tiny spinning-top gyroscope (but no bearing friction)
      • Under development since 1940’s
      • New opportunity for practicality leveraging CSAC technology
    • Atom-Interferometric (AI) Gyroscopes
      • Similar to fiber-optic gyroscope (FOG) and ring-laser gyroscope (RLG)
      • Use atom waves rather than light waves
      • Provides both gyroscopy and accelerometry
      • STO PINS/HiDRA program targeting extra-super performance
      • MTO C-SCAN targeting great performance in low C-SWaP

• **Technology gap:** Enabling atomic physics components
  • Nearly identical requirements as high-performance clocks, magnetometers, gravimeters, etc.
## Approach: Light Pulsed Atomic Interferometry

<table>
<thead>
<tr>
<th>AO Sense</th>
<th>Draper Laboratory</th>
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<tbody>
<tr>
<td>Dr. Matt Cashen</td>
<td>Dr. David M. Johnson</td>
</tr>
<tr>
<td><img src="image1.png" alt="Image of AO Sense" /></td>
<td><img src="image2.png" alt="Image of Draper Laboratory" /></td>
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<tr>
<td>Sandia National Labs</td>
<td>Honeywell</td>
</tr>
<tr>
<td>Dr. Grant Biedermann</td>
<td>Dr. Robert Compton</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image of Sandia National Labs" /></td>
<td><img src="image4.png" alt="Image of Honeywell" /></td>
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# Approach: Nuclear Magnetic Resonance

<table>
<thead>
<tr>
<th>Company</th>
<th>Contact Person</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northrop Grumman</td>
<td>Dr. Mike Larsen</td>
</tr>
<tr>
<td>Microsemi</td>
<td>Dr. Richard Overstreet</td>
</tr>
<tr>
<td>UC Irvine</td>
<td>Prof. Andrei Shkel</td>
</tr>
<tr>
<td>Princeton University</td>
<td>Prof. Mike Romalis</td>
</tr>
</tbody>
</table>
CAMS Objective:
Laboratory experiments have demonstrated that laser-cooled atomic clocks and inertial sensors are capable of extraordinary performance. Practical deployment of cold-atom sensors requires the development of enabling components. CAMS is a collection of seedlings developing low-CSWaP atomic wavelength lasers, optical isolators, shutters, vacuum cells, alkali vapor pressure control, and frequency control techniques.

Key Challenges:
• Maintain lifetime vacuum levels of 1nT without magnets
• Stabilization of alkali vapor pressure across mil-spec temperature range
• Fast, large aperture, shutters with extinction ratio >70dB
• Stable, single-mode, narrow-linewidth lasers at atomic transition wavelengths
• All at low-CSWaP
Thank you

Robert.Lutwak@darpa.mil