The Chip-Scale Combinatorial Atomic Navigator

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Future breakthroughs in microtechnology for positioning, navigation, and timing (PNT) will likely rely on yet-to-be-exploited physics, new materials, highly specialized fabrication technologies, and batch assembly techniques, selective wafer-level trimming and polishing, a combination of passive and active calibration techniques strategically implemented right on-chip, and introduction of innovative test technologies.

Such microtechnology advances for PNT are sought because reliance on satellite-based GPS for precision PNT information, which is critical to the conduct of many types of military operations and the performance of a wide range of military weapon systems, can mean dependence on a resource that may become inaccessible, whether as a result of some type of component or overall system malfunction or as a consequence of deliberate enemy action. The goal of the DARPA micro-PNT portfolio of programs is to develop microtechnology for self-contained, chip-scale inertial navigation and precision guidance that would effectively eliminate the dependence on GPS while enabling uncompromised navigation and guidance capabilities for advanced munitions and various military platforms, under a wide range of operation conditions.

In 2012, under the project name C-SCAN, DARPA solicited innovative research proposals in the area of co-integration of inertial sensors with dissimilar physics of operation in a single micro-scale inertial measurement unit (IMU). This solicitation is an integral part of DARPA's microtechnology for Positioning, Navigation, and Timing (micro-PNT) portfolio of programs. The overarching objective of the micro-PNT portfolio is to develop technologies for self-contained chip-scale inertial navigation and precision guidance that could effectively eliminate the dependence on GPS or any other external signals and enable uncompromised navigation and guidance capabilities for advanced munitions, mid- and long-range missiles, and various military platforms under a wide range of operating conditions. The micro-PNT program currently includes a number of important specific efforts that focus on development of precision timing devices, inertial sensors, and microsystems. C-SCAN leverages the results of these efforts and expands the scope of the micro-PNT program.

> A preferable [military] solution is to completely eliminate dependence on GPS or any other external signals during the mission.

In this context, the program sought to address challenges associated with the long-term drift, dynamic range, and start-up time of chip-scale components for positioning, targeting, navigation, and guidance tasks. Specific interest lies in the development of a Chip-Scale Combinatorial Atomic Navigator (C-SCAN) that combines inertial sensors with dissimilar, but complementary, physics of operation into a single microsystem. The main objectives of the C-SCAN program are to:

- explore miniaturization and co-fabrication of atomic sensors

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This columns builds on material presented in a September 2011 *GPS World* article, "Microtechnology Comes of Age," available at *www.gpsworld.com/microage*.

That article, also by Andrei Shkel, described:

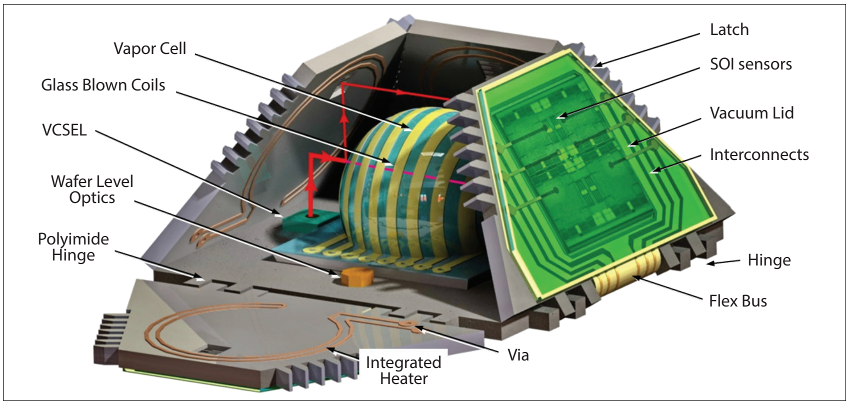
- two then-current efforts involving the development of clocks: Chip-Scale Atomic Clock (CSAC) and Integrated Micro Primary Atomic Clock Technology (IMPACT), and
- three efforts involving the development of inertial sensors and systems: Navigation-Grade Integrated Micro Gyroscopes (NGIMG), Micro Inertial Navigation Technology (MINT), and Information Tethered Micro Automated Rotary Stages (IT-MARS).

The article continued to explore four complementary new developments:

- Microscale Rate Integrating Gyroscopes (MRIG),
- Chip-Scale Timing and Inertial Measurement Unit (TIMU),
- Primary and Secondary Calibration on Active Layer (PASCAL),
- Platform for Acquisition, Logging, and Analysis of Devices for Inertial Navigation & Timing (PALADIN&T).

This column goes yet further, announcing the start of development of the Chip-Scale Combinatorial Atomic Navigator (C-SCAN) — the subject of a 2012 Broad Agency Announcement and request for proposals.

See related news story on one of several recipients of a C-SCAN grant online at *www.gpsworld.com/aosense*; it should not be viewed as the only technical approach paving the way.



▲ **FIGURE 1** C-SCAN conceptual implementation.

with high-performance solid-state inertial sensors, and

- develop combinatorial algorithms and architectures that seamlessly co-integrate components with dissimilar physics in a single ensemble.

The deliverable is a miniature IMU that co-integrates atomic and solid-state inertial sensors in a single microsystem with a volume of no more than 20 cubic centimeters (20 cc) and power consumption of no more than 1 Watt (1 W). The performance of C-SCAN is expected to be above and beyond what is currently available, combining a high resolution of motion detection (10^{-4} deg/hour for rotation and 10^{-6} g for linear acceleration), exceptional long-term bias and scale-factor stability (1 ppm with respect to the full-scale of operation), and start-up time performance orders of magnitude better than available today (less than 10 seconds from cold start).

To meet these objectives, the C-SCAN program expects to develop a complete IMU comprised of combinatorial gyroscopes and accelerometers with the following characteristics: 10^{-4} deg/hour and 10^{-6} g bias stability, $5 \cdot 10^{-4}$ deg/√hour angle random walk (ARW) and $5 \cdot 10^{-4}$ m/sec/√hour Velocity Random Walk (VRW), 1 ppm bias and scale-factor drift characteristics of 40 Hz (or ~15,000 deg/sec) and 1,000 g range of operation, respectively.

The C-SCAN module will have three axes of rotation, as well as three axes of acceleration sensitivity. The misalignment between the axes of sensitivity in C-SCAN is not to exceed 10^{-4} radians when operating in a harsh military environment. The operational environments of interest are:

- in-operation exposure to temperatures varying from -55ºC to +85ºC,
- in-operation exposure to mechanical vibrations from 5 Hz to 5 kHz with an average amplitude 5 g, and
- device survivability and subsequent normal operation after exposure to
  - 15,000 g shock exerted in less than 1 sec,
  - a peak acceleration amplitude on the level of 20 g through the frequency range for random vibrations from 5 Hz to 5 kHz, and
  - a 100ºC temperature difference thermal shock with transfer time not exceeding 10 seconds.

Current state-of-the-art microscale inertial instruments can provide the required level of precision for missions of only 30 seconds or less in duration. The micro-PNT program is developing chip-scale, small SWaP+C (Size, Weight and Power, plus Cost) inertial sensors for a variety of operational scenarios, missions ranging from minutes to hours, and for reliable operation under environmental conditions varying from moderate to severe. Ongoing work includes development of a broad range of chip-scale precision timing devices and inertial sensors, including chip-scale atomic clocks, chip-scale primary atomic clocks, solid-state oscillators, silicon accelerometers, and various gyroscopes: vibratory rate, rate-integrating, electrostatically levitated spinning-mass, micro-nuclear magnetic resonance, and cold-atom interferometric.

While recent results in the micro-PNT program have shown considerable progress toward development of small-scale inertial instruments approaching navigation-grade performance, the overall challenge remains: how to simultaneously meet all the stringent PNT requirements imposed by DoD missions in a small SWaP+C package. Specific requirements include, but are not limited to, accuracy, resolution, scale-factor and bias stability (both in-run and long-term), extended dynamic range, fast warm-up time, and short integration time. These challenges are significant, and it is unlikely that all the requirements can be achieved in a single type of device.

Overall, more than 98 percent of the missiles currently in the U.S. arsenal have mission durations of less than 20 minutes, and today, almost all of these missions are critically dependent on GPS for achieving the required level of delivery accuracy. A preferable solution is to completely eliminate dependence on GPS or any other external signals during the mission and rely solely on self-contained solutions such as inertial navigation, which is immune to jamming, spoofing, and other intentional or unintentional modification of position, orientation, and time information. Achieving 20 minutes of free inertial guidance is a major technological challenge faced by small SWaP+C inertial instruments. Solving this problem is of great strategic importance.

Several recent developments in micro-technology, inertial instruments, and atomic devices may present an opportunity for solving the problem of extended inertial guidance and navigation, potentially offering a new breed of chip-scale navigators exhibiting favorable characteristics when combined in a single hybrid micro-system ensemble.

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