

▲ **THE SIZE OF AN APPLE SEED:** The micro-PNT objective (conceptual illustration), a single-chip timing and inertial measurement unit, 8 mm³.

Microtechnology Comes of Age

The aggregated DARPA/MTO Microtechnology for Positioning, Navigation, and Timing (micro-PNT) program is pursuing a new wave of innovation focused on bringing to life revolutionary ideas and fabrication technologies on micro/nano/pico/femto/atto scales, packaging, ultra-low-power electronics, innovative algorithms, never-before-explored architectures, and exploitation of new integration paradigms.

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After about two decades of harmonic investment in developments, potential users of so-called small technology for positioning, navigation, and timing (PNT) applications increasingly ask, "Are we there yet?" Clearly, some significant advances have been made, and we see a footprint of the technology in an ever-growing consumer electronics market full of interactive products enabled by inertial and timing microtechnologies. These products include accelerometers for gaming applications, gyros for auto safety, resonators for clocks, and more.

The question remains, however: Is the technology really on the level of what we consider to be precision navigation and timing, that is, is it capable of achieving an accuracy level of at least 10 meters in position and 1 nanosecond in time throughout the entire duration of missions that may range from minutes to hours to days? In reality, small technology remains several orders of magnitude short with respect to

long-term stability, dynamic range, and accuracy compared to conventional technology, which is already known to perform adequately for many military applications.

Why does making inertial instruments and clocks small necessarily lead to degradation in performance?

We don't yet have a complete answer to this question, and we are still working hard to disprove the contention that high-performance inertial micro-instrument is a contradiction in terms. We can make things small, but we cannot yet make them sufficiently precise and uniform; the accuracy of lithography-based manufacturing is on the order of 10^{-2} – 10^{-3} (the ratio of the average defect to the smallest feature size), while the accuracy of conventional manufacturing utilizing precision machining is two to three orders of magnitude higher, on the order of 10^{-5} . We know we can deposit materials layer-by-layer with high precision, but we cannot make micro-devices truly 3D, as is

readily achievable using conventional machining. We consistently have an excellent case for low-cost and bulk fabrication, but we cannot seriously challenge so-called boutique processes when it comes to achieving precision, structural complexity, and long-term stability.

We need new knowledge regarding the dimensional stability of materials. We also need a better understanding of material scaling, surface effects, energy-loss mechanisms, and the consequences of fabrication imperfections on the performance of micro-instruments.

PNT applications demand both unusual new fabrication technologies and new materials with special properties. To achieve the required phenomenal accuracy for precision navigation and timing, we need a new wave of innovation in design and refinement of many existing transducers. Future breakthroughs in microtechnology for 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.

Need for Advanced Capabilities

PNT technology usage has doubled every five years since 1960, mostly due to GPS and the miniaturization of electromechanical components. Future PNT usage is expected to double every two years as a result of telecommunication, automobile navigation, robotics, and other commercial markets inserting micro-electromechanical systems (MEMS) technologies. The modern PNT paradigm is based on the assumption that space-based GPS is accessible most of the time to provide position, velocity, and timing information, enabling every

user to operate on the same reference system and timing standard.

Today's military systems increasingly rely on GPS, creating a potential vulnerability for U.S. and allied warfighters should GPS be degraded or denied. When GPS is inaccessible, critical information with respect to position, orientation, and timing can only be gathered through self-contained onboard instruments: a local clock and two triads of inertial sensors (three accelerometers for position and three gyroscopes for orientation). The ideal solution would be a self-sufficient instrument not relying on any external information. Precision microscale clocks and inertial sensors are required to address the paradigm of self-contained PNT.

Clocks. Position and time have a relationship important to a broad spectrum of military applications, including communication systems that feature efficient spectrum utilization, resistance to jamming, high-speed signal acquisition, and an increase in the period of autonomous operation. Other important applications include surveillance, navigation, missile guidance, secure communications, identification friend-or-foe, and electronic warfare.

The emerging applications require new compact time-distribution systems technologies capable of achieving signal phase (time) common synchronization of better than 10–9 seconds relative to the Coordinated Universal Time (UTC) standard; intersystem synchronization of less than 10–8 seconds relative to battle group; and less than 10–9 seconds for interoperability, surveillance, and high-speed communications. Solid-state and atomic oscillators are the key components enabling time and frequency distribution for communication, navigation, and command and control systems.

To support emerging applications, we are interested in clocks with

- signal phase (time) communication

synchronization less (better) than 28 nanoseconds (ns) within 5 minutes (real time), UTC;

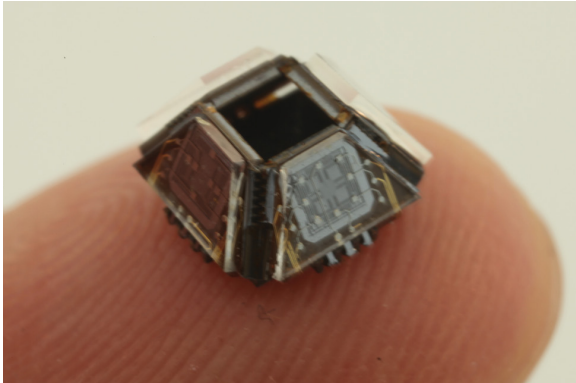
- intersystem synchronization less (better) than 28 ns relative to other system nodes within 5 minutes (real time); and
- local navigation/communication systems capable of time transfer less (better) than 28 ns, UTC.

The operational frequency mismatch ($\delta f/f$), where f is a nominal frequency and δf is a frequency deviation from the nominal, is a measure of oscillator quality and subsequently the quality of the frequency distribution system. Different applications can tolerate different levels of frequency mismatches. For example, for low-accuracy aircraft/land mobile platforms, the requirement for frequency mismatch is 10^{-12} , while for intermediate land reference sites the requirement is an order of magnitude smaller, 10^{-13} . For large time-division multiple-access (TDMA) systems, the tolerable frequency mismatch is on the order of 10^{-11} .

Small size, weight, and power (SWaP) are critical metrics for portable time and frequency distribution systems. The target performance characteristic for low-power clocks and oscillators is long-term stability (aging), which need to be less than 10^{-11} /month, with less than 1 W power consumption. It is desirable that the oscillators have small SWaP and preserve the level of long-term stability while surviving an inertial environment with accelerations on the level 10,000 g , where g is the gravity constant.

For comparison, the one-way satellite transmission from a GPS satellite in common view at two sites allows one to do accurate time transfer to within 10 ns, with a potential to achieve accurate time transfer of the order of 1 ns. Achieving an accuracy of time transfer on the level of 1 ns is loosely defined as precision timing.

Inertial Navigation Systems. The nav-



▲ **INITIAL PROTOTYPE** illustrating objective of the micro-PNT program.

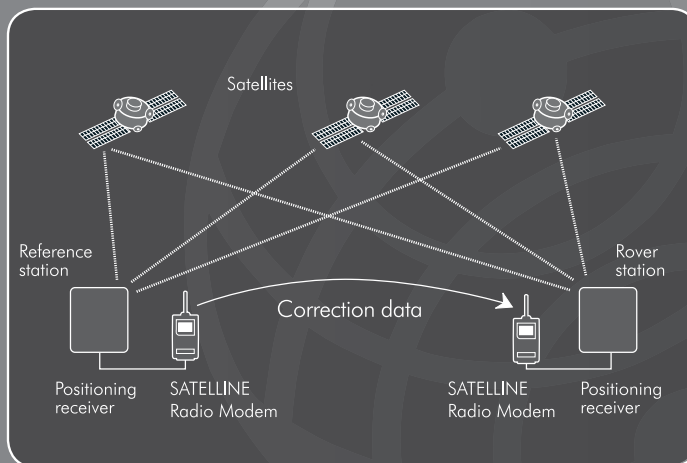
igation-grade performance provided by inertial sensors is defined as an INS that accumulates an uncertainty in location not greater than one nautical mile (nmi), or 1.852 km, after one hour of navigation. The error in position is historically defined by the circular error probable (CEP) of 50 percent. The ability to achieve a CEP of 1 nmi in one hour (or 1 nmi/hour) does not translate to a unique performance requirement for a gyroscope and/or an accelerometer. Rather, it presents a trade-off in the overall inertial measurement unit

(IMU) error budget. The trades can be generated within a family of gyroscope errors, such as gyro angle random walk (ARW) versus bias drift, or similarly within a family of accelerometer errors. For example, an IMU with gyroscope bias drift of 0.01°/hour combined with an accelerometer bias drift of 25 μg would guarantee a CEP of less than 1 nmi/hour, if no other errors are present. To generate the trade-off space for component performance, one efficient approach is to first generate the parameter space at the linear error covariance level, taking into account the bias drift of components, and subsequently perform more extensive modeling in a bounded trade-off space by a nonlinear Monte Carlo simulation.

The ability to navigate and keep precise timing has been an important factor in defining the military and economic power of nations for at least a millennium. For almost a century, the development of high-performance inertial instruments has been an extensive area of research. It is anticipated that the following level of performance will soon be achieved, significantly reducing navigation errors and enhancing military capabilities, within the next 5 to 10 years:

- < 0.1 nmi/hour CEP for aircraft, vehicle, or spacecraft for attitude, guidance, and control;
- < 1.0 nmi in 30 hours for ships;

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- < 0.4 nmi/hour CEP for missiles.

It is critical that future-generation INS systems be capable of operating through shock levels greater than 1,000 g.

Similar to clocks, the reduction of SWaP and cost (SWaP+C), while not compromising in performance, are the critical metrics for future development of IMUs. The current performance of state-of-the-art MEMS-based IMUs is on the level of tactical grade, with CEP approaching 100 nmi/hour. There is a great potential for achieving performance improvements that will subsequently enable platforms for personal navigation, precision navigation of small unmanned aerial vehicles (UAVs), unmanned underwater vehicles (UUVs), and GPS-free navigators for missiles. It is expected that the performance levels of chip-scale inertial instruments and clocks, shown in **TABLE 1**, could be achieved within the next 5 to 10 years, thus significantly enhancing military capabilities. The conservative estimations are projected by the Department of Defense's Science and Technology List for Positioning Navigation and Timing. The aggressive estimates presume successful completion of the micro-PNT program described here.

The military has access to a currently specified accuracy of 21 meters (95 percent probability) from the GPS Precise Positioning Service (PPS). Accuracy can be improved after calibration for some of the GPS errors, for example, by utilizing optimal estimation techniques correlating GPS and INS signals. A CEP of less than 10 meters has been routinely achieved, with a potential to achieve accurate positioning on the order of 1 meter CEP.

Navigation, guidance, and automatic control are not the only military applications that could benefit from improvements in inertial sensors. Azimuth or north-pointing determination systems include celestial devices, magnetic compasses, and inertial sensors. Utilization of gyroscopes to precisely determine orientation has a number of benefits attributed to their immunity to magnetic fields, speed of acquisition, and potentially small SWaP+C. For this purpose, a variety of inertial equipment is being explored, including IMUs, attitude-heading reference systems (AHRS), and gyrocompasses. Providing an azimuth or north-pointing accuracy of less (better) than 0.5 arc minute multiplied by secant latitude has the potential to significantly enhance military capabilities for many targeting applications, especially for anticipated mobile platforms.

Current Research

This section provides an overview of the ongoing efforts funded by DARPA (Defense Advanced Research Projects Agency)/MTO under the micro-PNT program.

Clocks. The potential payoff of the precision-clock technology developed by the program will enable ultra-miniaturized and ultra-low power absolute time and frequency references for applications such as nano/pico satellite

Key Parameters	Units	Conservative	Aggressive
Gyroscopes			
Angle rate bias stability (1σ)	°/hour	0.3	0.01
Drift rate stability	°/hour	1	0.1
Scale factor (1σ)	ppm	100	1
Range of operation	°/sec	± 1,440	± 15,000
Power consumption	mW	< 50	5
Accelerometers			
Acceleration bias stability (1σ)	μg	130	1
Scale factor (1σ)	ppm	130	100
Inertial measurement units			
Navigation error (CEP)	nmi/hour	5	1
power consumption	W	< 0.25	< 0.2
Chip-scale clocks			
Time loss at 1 min	ns	10	1
Time loss at 1 hour	ns	50	1.2
Time loss at 1 day	ns	100	5
Time loss at 1 month	ns	1000	30
Frequency retrace	-	10^{-11}	10^{-13}
Environmental characteristics			
Performance through shock	g	1,000	1,000
Survive shock	g	10,000	20,000

▲ **TABLE 1** Projected performance of chip-scale inertial sensors and clocks by 2015.

systems, UUVs, UAVs, wristwatch-size high-security UHF communicators, and jam-resistant GPS receivers.

There are currently two efforts within the micro-PNT program involving the development of clocks: Chip-Scale Atomic Clock (CSAC) and Integrated Micro Primary Atomic Clock Technology (IMPACT).

The goal of the CSAC effort is to create ultra-miniaturized, low-power, atomic time and frequency reference units that will achieve, relative to present approaches: more than 200× reduction in size (from 230 cm³ to <1 cm³); more than 300× reduction in power consumption (from 10 W to less than 30 mW); and matching performance (1×10^{-11} accuracy and 1 ns/day stability). This work, funded by DARPA since 2002, has been supporting 11 teams. The program is currently in its final phase and supports two performers, Symmetricom and Teledyne Scientific. Symmetricom has already demonstrated pilot units that are 1 cm³ in volume, consume on the order of 100 mW of power, and perform on the level of better than 30×10^{-11} short-term 1 sec instability (Allan Deviation) and 5×10^{-11} /day (1.4×10^{-10} /month) long-term frequency drift.

The IMPACT program seeks to improve the stability and accuracy of microscale atomic clocks by as much as two orders of magnitude. Atomic-clock performance is affected by buffer gases (nitrogen or argon), which are necessarily present in either rubidium- or cesium-based atomic clocks. Buffer gas atoms interact with alkali atoms and effectively shift the resonant frequency of atoms. Emerging atomic-clock technologies based on laser-cooled atoms and trapped ions could overcome the limitations of CSAC.

The goal of IMPACT is to create miniaturized, low-power, integrated micro primary atomic clock technology that will achieve significant reduction in size relative to conventional

clocks, but slightly larger than CSAC (volume less than 5 cm³ in final package, excluding battery); significant reduction in power relative to conventional clocks, but slightly greater than CSAC (50 mW); and two orders of magnitude increase in performance relative to CSAC (frequency accuracy 1×10^{-13} , Allan deviation at one-hour integration time, and stability characterized by 5 ns/day time loss). The work, funded by DARPA since 2008, currently involves four teams: Honeywell, Symmetricom, Sandia National Laboratories, and OE Waves.

The overall approach is based on sampling of atomic transitions at extremely low temperatures, requiring vacuum on the level of 10^{-9} Torr and the ability to trap atoms in a small volume. The technology has been previously demonstrated on a large scale, but transferring the technology to small scale is far from trivial, requiring major innovations. The effort has already demonstrated magneto-optical trapping in a 16 cm³ atomic cell, and chip-scale clocks implemented using cold atoms performing on the level, quality factor \times signal/noise ratio $\sim 2.6 \times 10^{10}$, time loss after 1 ms equal to 10^{-4} ns; after 1 second, 6×10^{-3} ns; after 1 hour, less than 10 ns; and after 24 hours, on the order of 100 ns. Frequency retrace was

demonstrated at the end of the phase on the level of 10^{-11} .

Inertial Sensors and Systems. There are currently three efforts within the micro-PNT program 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 NGIMG effort seeks to develop tiny, low-power, rotation-rate sensors capable of achieving performance commensurate with requirements for GPS-denied navigation of small platforms, including individual soldiers, unmanned (micro) air vehicles, unmanned underwater vehicles, and even tiny (for example, insect-sized) robots. By harnessing the advantages of microscale miniaturization, the NGIMG effort is expected to yield tiny (if not chip-scale) gyroscopes with navigation-grade performance characteristics: overall size less than 1 cm³ (no power source), power consumption less than 5 mW, ARW less than $0.001^\circ/\sqrt{\text{hour}}$, bias drift less than $0.01^\circ/\text{hour}$, scale factor stability on the order of 50 parts per million (ppm), full-scale range greater than $500^\circ/\text{sec}$, and bandwidth on the order of 300 Hz.

The NGIMG effort has been funded by DARPA since 2005, and work is currently being conducted by three teams: Northrop Grumman, Boeing, and Archangel Systems. The work has demonstrated several experimental prototypes (some, but not all, independently verified by the government) performing on the level of ARW $0.01^\circ/\sqrt{\text{hour}}$, and bias drift $0.05^\circ/\text{hour}$.

The MINT effort seeks to develop microscale low-power navigation sensors that allow long-term (hours to days) precision navigation in GPS-denied environments. The goal is to create high-precision, navigation-aiding sensors that directly measure intermediate inertial variables, such as velocity and distance, to mitigate the error growth encountered by integrating signals from accelerometers and gyroscopes alone. In addition to aiding sensors such as velocity sensors, the combination of microscale inertial sensors will be integrated to a form-factor of one or two integrated circuits. Such an integrated sensor suite will be incorporated into the sole of a shoe for accurate and precise velocity sensing using zero-velocity events during walking.

The final goal of MINT is to achieve an overall package and form-factor for a velocity sensor (excluding IMU) of less than 1 cm³, power consumption for the velocity sensor of less than 5 mW, 1-meter position accuracy after 36 hours of walking, and 10 $\mu\text{meter}/\text{second}$ velocity sensing bias per step. The effort has been funded by DARPA since 2008 and involves work by four teams: Carnegie Mellon University, Analog Devices, Northrop Grumman, and Case Western Reserve University/University of Utah. To date, the work has demonstrated positioning error on the order of 4 meters after 30 minutes of walking.

The goal of the IT-MARS program is to implement and



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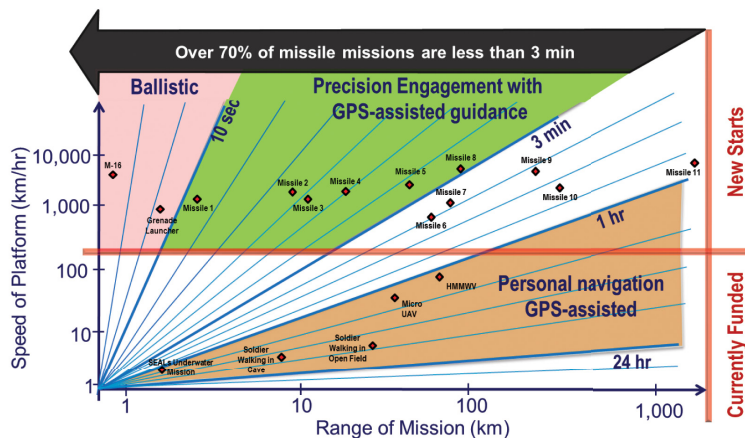
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▲ **FIGURE 1** Range of missions versus speed of platforms for common Department of Defense (DoD) needs. The duration of missions ranges from seconds to minutes to hours. The majority of missile missions are fast, but less than 180 seconds (3 minutes) in duration. All missions with duration greater than 10 seconds typically use GPS. The Micro-PNT program seeks to develop a single-chip solution enabling self-contained inertial navigation (without the need for external signals such as GPS) for diverse DoD scenarios.

demonstrate a MEMS-fabricated rotary stage providing a rotational degree of freedom to planar MEMS structures and sensors, thus enabling free rotation of micro-structures and micro-sensors relative to the package, with coupled power and signal transfer from the rotating platform to the package. The IT-MARS effort may enable highly accurate calibration of inertial sensors and serve as a micro-platform for carouseling of inertial sensors that further enable on-chip calibration and gyro compassing. The ultimate

program goal is to achieve an overall volume of no more than 1 cm³, power consumption for actuation on the order of 10 mW, angle position absolute accuracy to within 1 milli-degree, maximum wobble of 10 micro-radians, a rotation rate of 360°/second, and reliability (run time of rotor) greater than 10⁴ hours.

This effort, which has been funded by DARPA since 2009, supports three teams: UCLA, UC-Berkeley, and the Boyce Thompson Institute. The work has already demonstrated free rotated

platforms, and future efforts will focus on manufacturability and precision control of the stage-rotation and reduction of wobbling.

New Initiatives

In January 2010, DARPA/MTO launched a coordinated effort focused on the development of microtechnology specifically addressing the challenges associated with miniaturization of high-precision clocks and inertial instruments. The new program, Microtechnology for Positioning, Navigation, and Timing (micro-PNT), aggregated the existing efforts (CSAC, IMPACT, NGIMG, MINT, and IT-MARS) and initiated 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).

The overall goal of the new aggregated micro-PNT program is to focus all of these complementary efforts toward achieving one specific overarching

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goal: self-contained chip-scale inertial navigation (**OPENING ILLUSTRATION**). The reduction of SWaP+C of IMUs and timing units (TUs) is the technological objective. The developments consider a number of operational scenarios, ranging from dismounted-soldier navigation to navigation, guidance, and control (NGC) of UAVs/UUVs and guided missiles. The new micro-PNT initiatives will increase the dynamic range of inertial sensors, addressed by the new MRIG effort; reduce the long-term drift in clocks and inertial sensors, addressed by the PASCAL work; develop ultra-small chips providing position, orientation, and time information, addressed by the TIMU effort; and provide a universal and flexible platform for the testing and evaluation of components developed within the comprehensive micro-PNT program, addressed by the PALADIN&T effort.

The primary goal of MRIG is to create a vibratory gyroscope that can be instrumented to measure the angle of rotation directly, thereby extending the dynamic range and eliminating the need for integrating the angular rate information; MRIG will thus eliminate the accumulation of errors due to numerical/electronic integration.

The final goals are to:

- extend the dynamic range to 15,000°/second;
- achieve drift repeatability on the level of 0.1°/hour (angle dependent) and 0.01°/hour (bias-dependent) under variable -55°C to 85°C thermal conditions;
- achieve ARW of 0.001°/√hour, an operation range of 1,000 g with acceleration sensitivity of 10⁻⁵ degrees/hour/g, vibration sensitivity angle random walk of 0.01°/√hour per g/√Hz, and drift rate of 0.01°/hour per g²/√Hz.

These performance characteristics are thought to be achievable through development of precision 3-D fabrication technologies utilizing high-Q materials; development of

wafer-level balancing and trimming techniques that reduce the effects of aniso-inertia (mass misbalance), aniso-compliance (stiffness misbalance), and aniso-damping (damping misbalance); and development of active control and an active calibration architecture.

These performers have been selected for the initial phase of the MRIG effort: Draper Labs, Honeywell, Northrop Grumman, Systron Donner, UC-Irvine, UC-Davis, UCLA, Cornell, University of Michigan, and Yale University.

The TIMU effort will address challenges associated with the development of a miniature (10 mm³), low-power (200 mW), high-performance (CEP on the order of 1 nmi/hour), and self-sufficient navigation system on-a-chip. The smallest state-of-the-art IMUs perform on the level of tactical-grade instruments (CEP on the order of 100 nmi/hour) and are about the size of an apple (more than 10⁴ mm³). This effort intends to develop a technological foundation for a navigation-grade TIMU (CEP less than 1 nmi/hour and time accuracy of 1 nanosecond/minute) with a significant reduction in SWaP, potentially miniaturizing the TIMU to the size of an apple seed (10 mm³).

PASCAL will develop self-calibration technologies intended to eliminate long-term bias drift of inertial sensor and clocks. The grand challenge of this effort is to raise long-term bias stability to the level of 1 ppm.

This level of stability represents a two-orders-of-magnitude improvement compared to state-of-the-art inertial microsensors, currently at 200 ppm. The work will investigate an approach for fabricating sensors on an active layer that may serve as a calibration layer for micro-PNT systems.

The PALADIN&T effort will develop a universal platform for test and evaluation of early prototypes developed in the micro-PNT program. The effort will also simplify the uniform evaluation of pilot prototypes within the program and provide an

early field demonstration, advancing the technology readiness level.

Conclusions

Current state-of-the-art microscale clocks and inertial instruments can provide the required level of precision only for missions having a duration of no more than about one minute. The micro-PNT program at DARPA is developing small SWaP+C inertial sensors for a variety of operational scenarios for missions ranging from minutes to hours. Current projects (CSAC, IMPACT, NGIMG, MINT, IT-MARS) mainly focus on navigation, characterized as missions of prolonged durations in relatively benign environments (a few hours of operation on a platform moving at relatively low speed, less than 100 km/hour).

The new initiatives (MRIG, TIMU, PASCAL, and PALADIN&T) target the challenges of missile guidance for precision engagement scenarios, short duration missions in highly dynamic environments (10 seconds to 3 minutes of operation at speeds of 1,000 km/hour and higher). Ongoing efforts and new initiatives explore new physical phenomena, high-quality factor materials, specialized fabrication technologies, and innovative approaches to system integration.

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