Quantum Inertial Navigation Systems

Technology Trends
MQE

Motivation

Inertial navigation systems (INS) provide autonomous positioning by tracking acceleration and rotation without external references. While classical INS have reached impressive performance levels, they fundamentally suffer from drift error accumulation over time. All classical sensors show bias drift, with position errors growing quadratically with time, making unaided navigation beyond several hours challenging even with high-end systems.

Quantum inertial sensors promise to dramatically reduce this drift by exploiting quantum mechanical properties of atoms. Unlike manufactured devices with inevitable tolerances and aging effects, quantum sensors use atoms as inherently stable, atomically identical test masses whose properties are defined by fundamental constants.

Classical INS Core Components

In inertial navigation systems, there are two main components that work together to track movement in space:

Accelerometers measure linear acceleration along sensitive axes. Key classical technologies include:

- **Mechanical pendulums:** Force-rebalance systems with proof masses on flexures
- **MEMS accelerometers:** Micro-fabricated structures whose capacitance changes with acceleration
- **Optical accelerometers:** Measure displacement of proof mass using interferometry

Gyroscopes measure angular velocity. Key classical technologies include:

- **Ring Laser Gyroscopes (RLG):** Two counter-propagating laser beams experience frequency shifts proportional to rotation (Sagnac effect)
- **Fiber Optic Gyroscopes (FOG):** Similar physics to RLG but using fiber coils
- **Hemispherical Resonator Gyros (HRG):** "Wineglass" resonator whose vibration pattern rotates with input rotation
- **MEMS gyros:** Vibrating structures that experience Coriolis force when rotated

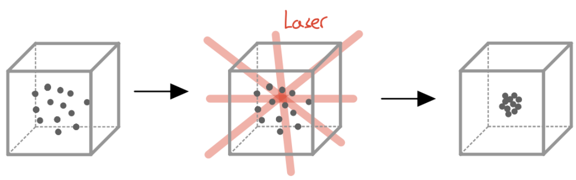
Cold-Atom Interferometry

The leading quantum approach uses cold atoms as test masses in matter-wave interferometers. This provides an absolute measurement referenced to atomic properties, significantly reducing long-term drift. While there are many different concepts for implementing cold-atom interferometry, we will explain a simple free-fall implementation.

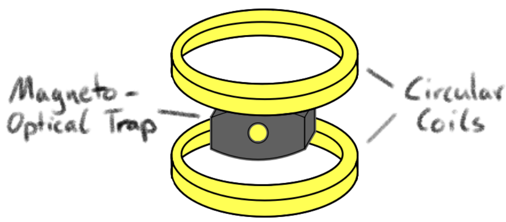
The process involves the following key steps:

a.) Laser cooling of atoms to near-absolute zero [2]
b.) Atoms entering free-fall state
c.) Three-pulse interferometer sequence [1]
d.) Reading out the phase shift
e.) Deducing translation or rotation from phase information [3]

Laser Cooling: First, atoms (typically Rubidium-87 or Cesium-133) are cooled to near absolute zero using laser cooling techniques:

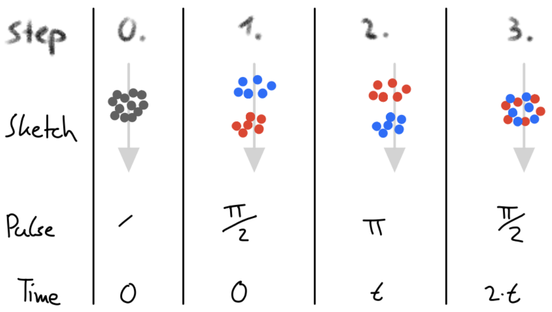


Free-Fall State: Atoms are held in a magneto-optical trap between coils. When coils are turned off, atoms enter free-fall:



Three-Pulse Interferometer Sequence: The core sensing mechanism uses a sequence of laser pulses to create and manipulate quantum superpositions:

0. **Preparation:** Atoms are prepared in a specific quantum state while in free-fall
1. **First Pulse ($\pi/2$ - "Beam Splitter"):** Creates superposition of two momentum states
2. **Second Pulse (π - "Mirror"):** Reverses momentum difference between paths
3. **Third Pulse ($\pi/2$ - "Recombiner"):** Interferes paths, encoding inertial effects as phase shift



The phase difference measured after this sequence is directly proportional to acceleration:

$$\Delta\phi = k_{eff} \cdot a \cdot T^2$$

Where k_{eff} is the effective wavevector, a is acceleration, and T is time between pulses. For rotation sensing, the phase shift follows the Sagnac effect, proportional to:

$$\Delta\phi \approx \frac{2m}{\hbar}\Omega \cdot A$$

Where Ω is rotation rate and A is the enclosed area. Multi-axis sensing requires either multiple atom interferometers or sophisticated pulse sequences.

Other Quantum Inertial Sensing Approaches

Nuclear Magnetic Resonance Gyroscopes (NMRG): These use spin precession of noble gas nuclei (e.g., Xe-129, Xe-131) to detect rotation, canceling magnetic field effects through comparison of isotope pairs. NMRGs have reached navigation-grade performance in compact packages with bias stability ¡0.02°/h [4].

Nitrogen-Vacancy Diamond Gyroscopes: Solid-state approach using quantum sensing with nitrogen-vacancy centers in diamond. Nuclear spins in diamond detect rotation via precession frequency shifts. Currently less sensitive than NMRGs but promising for miniaturization [4].

Trapped Ion Interferometers: Use charged atoms in electromagnetic traps with superpositions of different orbital paths to sense rotation via Sagnac effect. Could enable high sensitivity in small packages but remain at early research stage.

Quality Comparisons

Accelerometers

Technology	Quality (Bias Stability)
Mechanical (Servo Pendulum)	Few µg
Optical Interferometric	∼1 µg
MEMS (Tactical)	∼50 µg
MEMS (Consumer)	Hundreds of µg
Quantum (Cold-Atom)	**∼0.07 µg (after 2 days)**

Gyroscopes

Technology	Quality (Bias Stability)
Ring Laser (RLG)	∼0.001–0.01 °/h
Fiber Optic (FOG)	∼0.01–1 °/h
Hemispherical Resonator (HRG)	∼0.001–0.01 °/h
MEMS	∼1–1000 °/h
Nuclear Magnetic Resonance (NMRG)	**∼0.02 °/h**
Cold-Atom Quantum	**∼0.0002 °/h**

Performance data for classical gyroscopes from [5], for classical accelerometers from [6], for quantum accelerometers from [1,2], and for quantum gyroscopes from [3,4].

Current Challenges

Size, Weight, and Power (SWaP): Current cold-atom systems require vacuum chambers, laser systems, and extensive control electronics, making them significantly larger than classical equivalents. Atomic devices typically occupy volumes of several liters and consume tens of watts.

Bandwidth and Dynamic Range: Quantum sensors operate at low frequencies (1-10 Hz) compared to classical sensors (100-1000 Hz). The interferometer cycle (cooling, interferometry, detection) takes 0.1-1 seconds, creating "dead time" and limiting dynamic range in high-motion environments.

Environmental Sensitivity: Quantum states are vulnerable to magnetic fields, vibrations, and temperature fluctuations. Extensive shielding and noise-cancellation strategies are required for field operation.

Complexity: Current systems require expertise in atomic physics, lasers, vacuum systems, and control electronics. Efforts to develop turn-key systems are ongoing but not yet widely available.

Quantum Advantages

Source of superior performance: Quantum sensors excel because:

- All atoms of the same isotope are completely identical (no manufacturing variability)
- Measurement is directly referenced to fundamental physical constants
- Atomic properties don't drift over time (unlike mechanical components)
- Coherent quantum superposition enables extreme sensitivity to inertial effects

These properties translate to nearly zero-bias operation over long time periods. While classical sensors might have lower noise over short timescales, their bias drift accumulates, while quantum sensors maintain their accuracy indefinitely.

The most promising deployments use hybrid systems: classical sensors provide high-bandwidth measurements and handle dynamic conditions, while quantum sensors periodically recalibrate them to eliminate long-term drift.

Recent experiments demonstrate this approach works: a 2024 ONERA study showed a hybrid quantum-classical IMU reduced accelerometer drift by 100$\times$ and gyroscope drift by 3$\times$ compared to the classical IMU alone [1].

Applications

GPS-Denied Navigation: The primary application is enabling precise navigation when satellite signals are unavailable:

- **Submarine Navigation:** Quantum IMUs could allow submarines to remain submerged for weeks while maintaining positional accuracy
- **Gravity Mapping:** Quantum gravimeters can detect local gravity variations for position fixing via map matching
- **Space Navigation:** Drift-free inertial guidance for deep space missions beyond GPS coverage
- **Military Operations:** Resilience against GPS jamming or spoofing in contested environments
- **Underground/Indoor Navigation:** Accurate positioning where satellite signals cannot penetrate

Key Players: Major efforts include AOSense and Vector Atomic (USA), Exail/Muquans (France), and ColdQuanta/Infleqtion (USA/UK), alongside research at ONERA, NRL, and various academic institutions.

References

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