Cold Atom Navigation Sensors

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Navigation strategies

- **Radio navigation**
  - Radio reference signals allow trajectory determination (e.g., GPS)

- **Inertial navigation**
  - Trajectory determination with accelerometers and gyroscopes
  - “Black-box”

- **Integrated Radio/Inertial**
  - System initialization with radio
  - Inertial sustains navigation solution over radio lapses

Galileo constellation

HG 1900 series IMU
Next generation integrated INS/GPS

Integration of RF satellite, inertial, and clock sensors into one quasi-optimal Navigation, Attitude, Time estimator

Diagram courtesy of Jim Spilker
• Early in 20\textsuperscript{th} century, prominent physicists argued against INS, citing Equivalence Principle
  – “problem of the vertical”

• Best inertial sensors are mechanical
  – MEMS, ring-laser and fiber-optic gyro have yet to be incorporated in very high performance systems
Physics of space-time

- GP-B
  - gravitational warping of space-time
- LIGO
  - gravitational waves
- LISA
  - space-based gravity wave antenna
- ...

 Physics packages for these experiments have superb sensors.

Sensors are unsuitable for navigation.
And yet ....

- Atomic physics community is evolving a new class of inertial sensors based on de Broglie wave interference which appear to enable low cost, robust, high accuracy INS
de Broglie wave sensors

Gravity/Accelerations
As atom climbs gravitational potential, velocity decreases and wavelength increases

Rotations
Sagnac effect for de Broglie waves

Current ground based experiments with atomic Cs:
Wavepacket spatial separation ~ 1 cm,
Phase shift resolution ~ 10^{-5} rad
1 rad phase shift for 10^{-7} g acceleration or 0.1 Earth rate rotation
(Light-pulse) atom interferometry

Resonant optical interaction

Resonant traveling wave optical excitation, (wavelength $\lambda$)

Recoil diagram

Momentum conservation between atom and laser light field (recoil effects) leads to spatial separation of atomic wavepackets.
Laser cooling techniques are used to achieve the required velocity (wavelength) control for the atom source.

**Laser cooling:** Laser light is used to cool atomic vapors to temperatures of ~10^{-6} deg K.

Image source: www.nobel.se/physics
Atom is in a near perfect inertial frame of reference (*no spurious forces*).

Laser/atomic physics interactions determine the relative motion between the inertial frame (defined by the atom deBroglie waves) and the sensor case (defined by the laser beams).

Sensor accuracy derives from the use of optical wavefronts to determine this relative motion.
Sensor characteristics

**Light-pulse AI accelerometer characteristics**

- Bias stability: $<10^{-10}$ g
- Noise: $4\times10^{-9}$ g/Hz$^{1/2}$
- Scale Factor: $10^{-10}$

**Light-pulse AI gyroscope characteristics**

- Bias stability: $<60$ μdeg/hr
- Noise (ARW): 3 μdeg/hr$^{1/2}$
- Scale Factor: $<5$ ppm

Laboratory gyroscope (1997)

AI gyroscope

ARW \(3 \mu \text{deg/hr}^{1/2}\)

Bias stability: \(< 60 \mu \text{deg/hr}\)

Scale factor: \(< 5 \text{ ppm}\)

Atom shot noise

Gravity gradiometry and high accuracy navigation

Gravity gradiometer enables real-time discrimination of gravity-induced accelerations from platform accelerations.

Required for high accuracy navigation in near (un-mapped) gravity anomalies.
Laboratory gravity gradiometer (2002)

Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.

Demonstrated differential acceleration sensitivity:

$4 \times 10^{-9} \text{ g/Hz}^{1/2}$

$(2.8 \times 10^{-9} \text{ g/Hz}^{1/2} \text{ per accelerometer})$

(McGuirk, et al., PRA, 2002)
Measurement of Newton’s Constant

Pb mass translated vertically along gradient measurement axis.
Measurement of G

Systematic error sources dominated by initial position/velocity of atomic clouds.

\[ \frac{\delta G}{G} \sim 0.3\% \]

New instrument (2007)

Currently achieved statistical sensitivity at $\sim 2 \times 10^{-4} \text{ G}$ ($10^{-12}$ g acceleration resolution).
Multi-function sensor measures rotations and linear accelerations along a single input axis.

Interference fringes are recorded by measuring number of atoms in each quantum state.
Navigation performance

Determine geo-located platform path.

Necessarily involves geodetic inputs

Simulated navigation solutions.
5 m/hr system drift demonstrated.
Optimal phase retrieval

Interferometer outputs and noise model:

\[ y_A(k) = c_{1,A}(k) + (1 + c_{2,A}(k)) \sin(\phi_d + \phi_c(k) + c_{3,A}(k)) \]
\[ y_B(k) = c_{1,B}(k) + (1 + c_{2,B}(k)) \sin(\phi_c(k)). \]

**Previous:** Outputs parametrically describe an ellipse. Use non-optimal ellipse specific fitting to extract relative phase (McGuirk, Opt. Lett., 2001).

**New:** Use Bayesian estimation to optimally determine relative phase (Stockton, submitted).
Optimal Bayesian Phase Estimation vs. Ellipse Fitting

Numerical simulation to compare performance of Bayesian vs. ellipse specific methods for white, non-common, phase noise.

Bayesian method integrates as $t^{-1/2}$ without systematic error offset

Currently investigating computationally efficient implementations.

Suppresses systematic offsets in phase determination
Airborne Gravity Gradiometer: BHP FALCON Program

Existing technology

Sanders Geophysics

Land: 3 wks.

AI sensors potentially offer 10 x – 100 x improvement in detection sensitivity at reduced instrument costs.

LM Niagra Instrument

Air: 3 min.
Co-falling $^{85}\text{Rb}$ and $^{87}\text{Rb}$ ensembles

Evaporatively cool to $< 1 \, \mu\text{K}$ to enforce tight control over kinematic degrees of freedom

Statistical sensitivity

$\delta g \sim 10^{-15}$ with 1 month data collection

Systematic uncertainty

$\delta g \sim 10^{-16}$ limited by magnetic field inhomogeneities and gravity anomalies.

Also, new tests of General Relativity
Equivalence Principle Installation
Gravity-wave detection

Earth-based detectors (blue and red indicate two AI geometries)

Atom interferometer detectors

Space-based detectors (blue and red indicate two AI geometries)

Electron-proton charge balance

- Apparatus will support >1 m wavepacket separation
- Enable ultra-sensitive search for charge electron/proton charge.

\[ \varepsilon \equiv \frac{\delta e}{e} \sim 10^{-30} \]

Current limit: \( \frac{\delta e}{e} \sim 10^{-22} \)

(Unnikrishnan et al., Metrologia 41, 2004)

Impact of an observed imbalance currently under investigation.

Theory collaborators:
A. Arvanitaki, S. Dimopoulos, A. Geraci
Future technology: Quantum Metrology

Atom shot-noise limits sensor performance.

Recently evolving ideas in quantum information science have provided a road-map to exploit exotic quantum states to significantly enhance sensor performance.

- Sensor noise scales as $1/N$ where $N$ is the number of particles
- "Heisenberg" limit
- Shot-noise $\sim 1/N^{1/2}$ limits existing sensors

Challenges:
- Demonstrate basic methods in laboratory
- Begin to address engineering tasks for realistic sensors

Impact of successful implementation for practical position/time sensors could be substantial.

Enables crucial trades for sensitivity, size and bandwidth.
Quantum non-demolition atom detection

Dispersive cavity shift

Rabi oscillations detected via cavity shift

Thanks

Current team:

- Boris Dubetsky, Research Scientist
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