

Challenge Problem: Quantum Sensing

RTRC: Rodrigo Castillo-Garza and Amit Surana

QuantumCT: Vivek Ramakrishnan

Introduction

Quantum sensors exploit quantum mechanical phenomena found in quantum light and light-matter interactions to surpass classical limits and generate novel functionalities and sensing paradigms. For instance, using quantum light may increase signal-to-noise ratio in sensing platforms that use optical readouts that are limited by classical photon noise. Sensors using light-atom interactions like Rydberg vapor sensors and optical pump magnetometers may be able to reduce substantially the footprint of the state-of-the-art sensing platforms while increasing or maintaining their sensitivity and operational bandwidth. Other sensors, exploiting interaction between light and solid-state systems, e.g., magnetometers based on color centers may be used in extreme environments where it is critical to determine magnetic fields with high spatial resolution, and may offer more scalable solutions than quantum sensors based on light-atom interactions.

Physical and Engineering Bottlenecks

Laboratory quantum sensors have moved beyond proof-of-concept demonstrations. The key challenge now is maintaining the quantum advantage under realistic operational conditions—vibration and shock, extreme temperatures, wide thermal swings, radiation exposure, etc.—and on platforms constrained by low size, weight, and power consumption (SWaP).

Environmental effects and application-specific constraints remain the primary bottlenecks to deploying quantum sensors outside the laboratory. Thermal swings, for example, can induce stress-related birefringence in optical components, degrading sensor performance and disrupting supporting technologies such as photonic integrated circuits and laser sources. Likewise, vibration in operational platforms can decouple the interaction between lasers and atomic, molecular, or solid-state systems, rendering the sensors unusable even when active control techniques are employed.

Enabling Technologies

To reduce SWaP while preserving quantum advantage, applications require, for example, technologies that reduce the footprint of optical sources and optical paths between materials/atoms and laser sources. They need to generate and transport high-power light with minimal loss in wavelengths that match the electronic transitions of materials/atoms/molecular systems. Similarly, applications need robust optical chambers capable of containing and keeping atomic or molecular vapors at specific pressures and temperatures. These components must be scalable and resilient to the environmental conditions imposed by real-world applications.

To increase sensor robustness, quantum sensing technologies may develop robust sensing schemes that are rooted in novel materials, engineered light-matter interaction, novel schemes that reduce dephasing mechanisms, integrated electronic and optical systems, and/or novel compensation mechanisms that include AI algorithms to achieve required performance.

Research Themes

QuantumCT and RTRC are seeking collaborators to work on novel quantum sensing and materials around the themes below.

Theme 1. Magnetic-aided inertial navigation

Magnetic-aided inertial navigation (MAIN) enhances inertial systems by fusing IMU outputs with measurements of Earth's magnetic field or local magnetic signatures, providing an additional absolute or relative reference to constrain drift. MAIN offers advantages such as passive operation, resistance to GPS denial, applicability in indoor or subterranean environments, and compatibility with low-SWaP platforms. By exploiting stable geomagnetic models or locally characterized magnetic maps, MAIN can significantly improve long-term position and orientation accuracy beyond what IMUs alone can sustain. However, practical deployment faces challenges including magnetic field variability across geographic regions, distortion from nearby ferromagnetic materials or platform electronics, the need for high-quality magnetic maps, and robust fusion algorithms capable of rejecting magnetic anomalies while maintaining reliable state estimation.

Theme 2. Radio Frequency signal detection with Rydberg atom sensors

Rydberg-atom radio frequency (RF) sensors offer an atomically referenced and optically readout approach to electric-field detection, providing advantages such as electrically subwavelength operation, intrinsic absolute calibration, and broad spectral tunability within compact low-SWaP architectures. These capabilities make them attractive for applications in communications, spectrum awareness, navigation, and imaging. However, their deployment remains limited by challenges in achieving competitive sensitivity, dynamic range, and linearity relative to classical RF systems, maintaining stable performance under environmental stressors, and integrating quantum-derived field measurements with conventional RF front ends and digital signal-processing pipelines.

Theme 3. Quantum-enabled distributed sensing

Quantum-enabled distributed sensor network arrays combine devices—such as optical clocks, magnetometers, and interferometers—into coordinated architectures that use shared timing and phase references to surpass classical sensing limits for spatiotemporal monitoring. These networks offer broader spatial coverage, improved signal discrimination, and resilience through node-level redundancy. Their deployment, however, is constrained by the need to maintain quantum performance under environmental stressors, achieve ultra-stable synchronization across optical or RF links, miniaturize photonic and atomic subsystems to meet SWaP requirements, and ensure scalable fabrication and long-term stability across all nodes in real-world operating conditions.

Theme 4. Biological systems with quantum processes

Biological systems that exhibit or support quantum processes offer unique opportunities for advanced technologies, as certain biomolecules and structures—such as chromophore networks, spin-active proteins, and proton-tunneling pathways—can maintain quantum coherence, enable

efficient energy transport, or perform ultra-sensitive interactions that surpass classical limits. These naturally occurring quantum effects provide advantages including operation at ambient conditions, adaptive self-assembly, and compatibility with soft, irregular environments where engineered quantum systems often struggle. However, leveraging biological quantum phenomena for applied technologies remains challenging due to the fragility of coherence within dynamic biological media, variability across biological specimens, and the difficulty of creating stable, scalable interfaces between living or bio-derived quantum components and engineered platforms.