

QUANTUM SENSING IN CANADA

SUMMARY: This article examines the physical systems underlying prominent emerging quantum sensors, highlighting their achievements and opportunities across key Canadian sectors.



By **ERIKA JANITZ**¹ <erika.janitz@ucalgary.ca>,
PAUL BARCLAY² <pbarclay@ucalgary.ca>,
LILIAN CHILDRESS³ <lilian.childress@mcgill.ca>

¹Department of Electrical and Software Engineering, University of Calgary, Calgary, Alberta, T2N 1N4, Canada

²Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, T2N 1N4, Canada

³Department of Physics, McGill University, Montreal, Quebec, H3A 2T8, Canada

Quantum sensing exploits control over the quantum states of light or matter to engineer measurement devices with capabilities surpassing those of classical hardware. For example, quantum probes can suppress noise, enable nanoscale spatial resolution, or exploit entanglement to pick out weak signals from a noisy background. Here, we examine the techniques and applications of quantum sensing from a Canadian perspective, highlighting the work of Canadian institutions and companies while focusing on the role that quantum sensing could play in sectors relevant to the Canadian economy.

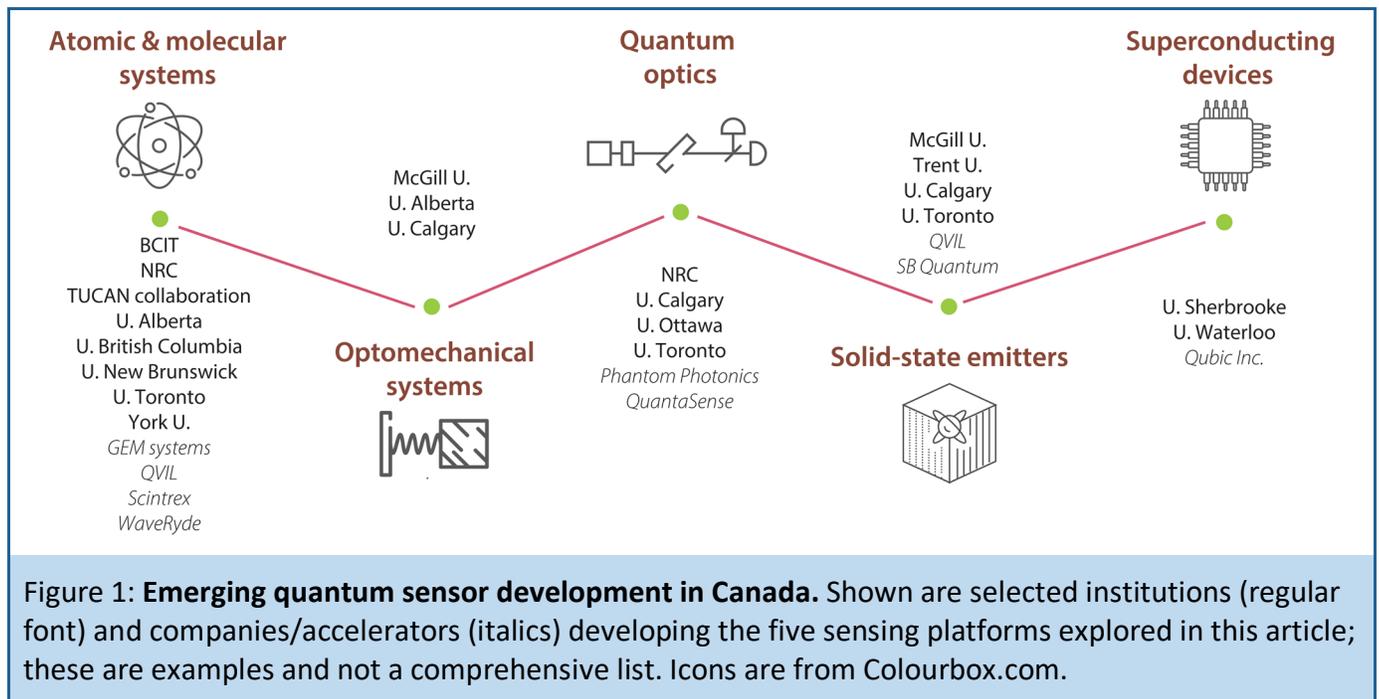
Despite strong and growing interest in the field, the definition of quantum sensing is not always clear. A recent review [1] proposed the following indicators: (1) Employing quantized energy levels, e.g., utilizing the energy shift of spin states to detect a magnetic field (2). Using quantum coherence or superposition, like in atomic matter-wave interferometry for measuring acceleration [2]. (3) Exploiting quantum entanglement, e.g., using entangled photons for improved target detection [3]. While the third category is the most unequivocally non-classical, we consider all three types of quantum sensors here. Nevertheless, this article's scope is limited to emerging quantum sensing modalities, omitting discussion of more mature platforms, such as traditional spectroscopy techniques (e.g., NMR, EPR, and optical) and scanning tunnelling microscopy.

PHYSICAL PLATFORMS

Canadian researchers and entrepreneurs are developing quantum sensors across the following physical platforms (Fig. 1).

Atomic and molecular sensors [4] exploit long-lived states of atoms or molecules whose transition frequencies can be probed with unparalleled precision (reaching below a part in 10^{18} [5]) using resonant electromagnetic fields. While unperturbed atomic transitions provide the basis for modern time standards [6], energy-level shifts induced by external electromagnetic fields permit extraordinarily sensitive magnetometry [7] and electrometry [8]. Gravitational fields, acceleration, and rotation affect the phase of atomic states and can be measured using atomic matter-wave interferometry [9]. Owing to their perfect reproducibility, long coherence times, and precision optical control techniques, atomic sensors offer promising solutions when absolute and/or ultra-high-precision measurements are required [4].

Optomechanical systems employ the radiation pressure force imparted by photons to control the quantum states of mechanical oscillators or engineer the quantum state of light interacting with the oscillator. Such systems can probe force, displacement, strain, mass, acceleration, magnetic fields, gravitational waves, and more [10]. Quantum enhancement of optomechanical sensors by squeezed light has been realized, most notably in the LIGO gravitational wave detector [11]. The ability to interact with a wide variety of targets makes optomechanical devices particularly versatile [12], for example, in using single vibrational quanta to probe microscopic electronic material phenomena [13]. Future goals include advancing classical optomechanical sensors, such as those for studying single molecules [14] and quantum materials [15], to a regime where quantum states of light are required to reach the ultimate limits in sensitivity.



Quantum optical sensors exploit quantum states of light to enhance imaging resolution or detection sensitivity, which is particularly beneficial for noisy or low-light environments. For example, by illuminating a target with photons entangled with a reference, one can exploit their quantum

correlations to isolate the signal in the presence of significant classical noise for improved imaging [16]. Alternatively, squeezed light exhibits fluctuations below the classical limit, offering enhanced signal-to-noise [17], which is especially relevant for objects that cannot tolerate intense irradiation. Ultimately, the variety of possible quantum-optical states and sensing modalities has led to a diverse range of protocols and applications.

Solid-state emitters, including atomic defects in diamond and two-dimensional materials, rare earth ions in solids, and quantum dots, can exhibit atomic-like properties and nanoscale spatial resolution that can be harnessed for sensing [18-20]. Solid-state emitters are also localized in materials amenable to device fabrication [21]. Many offer long-lived spin states, and some, such as the nitrogen-vacancy center in diamond, can operate in ambient conditions. As with atoms, external electromagnetic fields induce shifts in spin-state energies [22], but solid-state systems can also detect material properties that atoms cannot easily probe, such as temperature [23] and strain [24]. While spin ensembles provide greater sensitivity [25], individual solid-state emitters have realised spatial resolution on the 10-nm scale [26], and diamond defects have been incorporated into nanoparticles for intracellular sensing [27].

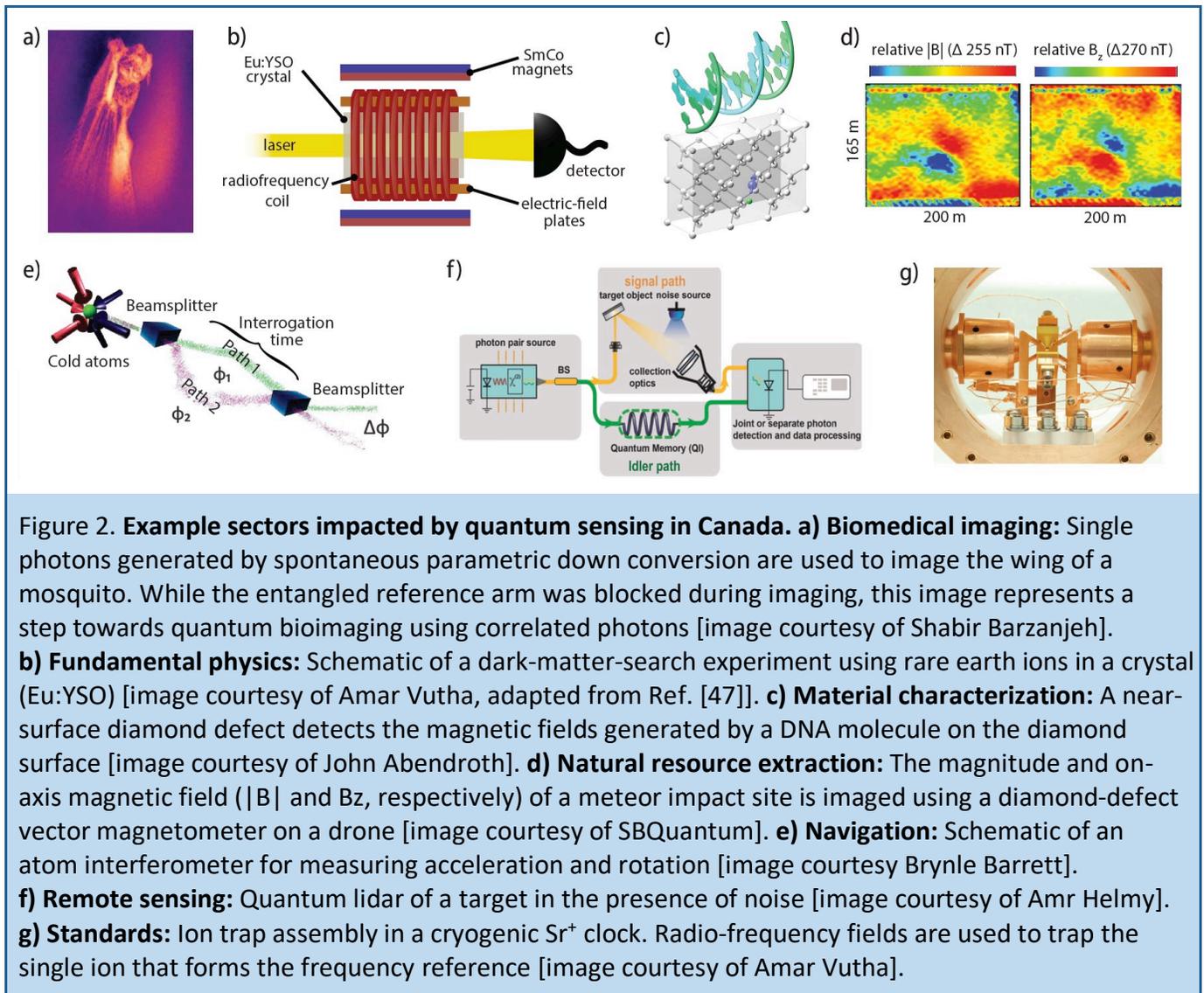
Superconducting devices leverage recent advances in superconducting materials, qubits, and resonators to offer compelling solutions for magnetometry and microwave quantum sensing when cryogenic operation is feasible. Superconducting quantum interference devices (SQUIDs) detect the magnetic flux in a superconducting ring broken by a Josephson junction [28], offering sensitive measurements from macro- to nanoscales [29]. Alternately, coherent interactions between superconducting qubits and microwave resonators can be used to engineer the quantum states of microwave fields, facilitating quantum-enhanced radar [30].

SECTORS IMPACTED

In this section, we give examples of how emerging quantum sensors offer essential capabilities for many of Canada's economic sectors and highlight efforts by Canadian institutions and companies in each area (Fig. 2).

Biomedical imaging is poised to benefit from quantum optical techniques, particularly for light-sensitive samples. Researchers at the University of Ottawa (UOttawa) and the National Research Council Canada (NRC) have used entangled photons for quantum-enhanced phase imaging to determine the thickness of transparent objects [31,32], which could be applied to biological systems such as cells. Entangled photons have also been used at the University of Calgary (UCalgary) and start-up QuantaSense to perform multilayer imaging [33], enabling complex structural analysis of biodegradable and photosensitive materials.

Fundamental physics can exploit the enhanced precision of quantum sensors to advance our understanding of physical laws. For example, ultra-high-precision quantum magnetometry at the University of Alberta (UALberta) could test theories of quantum gravity [34], while dark matter interactions could be constrained by optomechanical detection of superfluid helium acoustic modes at



McGill University and UAlberta [35] or by symmetry violations in rare earth ions in crystals at the University of Toronto (UToronto) [36]. Atomic experiments at York University (YorkU) have determined the hydrogen Lamb shift [37], the proton charge radius [37], and measured the fine structure of atomic helium [38], and a cesium magnetometer will aid measurement of the neutron electric dipole moment in the TUCAN collaboration with TRIUMF [39]. Finally, Canadian physicists have also been at the forefront of studies probing the fundamental limits to quantum measurement [40-42].

Material characterization can benefit from quantum sensors with nanoscopic resolution and sensitivity to internal material properties. For example, individual diamond defects have been used to probe nanoscale magnetic circuits at McGill [43,44], are being used for molecular [45] and material strain sensing [46] at UCalgary, and are being explored for nano-thermometry at Trent University (TrentU)

[47-48]. In addition, research at Université de Sherbrooke (USherbrooke) has contributed to thermometry in the 10-mK range using superconducting qubits [49].

Natural resource extraction relies extensively on magnetic and gravitational mapping to identify promising deposits. Commercial atomic magnetometers are produced by GEM Systems and Scintrex; magnetometers based on diamond-defect ensembles promise accurate vector-field sensing, with development at UCalgary [50] and McGill [51], and commercialization for mineral exploration by start-up SBQuantum [52] with support from USherbrooke [52]. At the same time, atomic interferometer measurements of local gravitational acceleration could provide high-precision subsurface density estimates for resource identification, aided by research at the University of New Brunswick (UNB) [2] and YorkU [54]. Finally, quantum sensors could impact post-extraction monitoring, for example, in a project on pipeline integrity monitoring from UAlberta and Synergy Aviation Inc. [53].

Navigation requires determining position and orientation with high sensitivity and accuracy. Inertial or magnetic navigation with quantum sensors could offer immunity to jamming and operation in GPS-denied or otherwise challenging environments. Several diamond-defect-based platforms are being pursued, including magnetometers from SBQuantum and gyroscopes from accelerator Quantum Valley Ideas Lab (QVIL). At the same time, researchers at UNB are developing atom interferometry for acceleration and rotation detection [2,55]. Alternately, SBQuantum's magnetometer may aid future refinements of the World Magnetic Model that underlies conventional navigation systems [56].

Remote sensing harnesses quantum techniques to enhance covert surveillance, detect sensitive objects, and image underwater or in space. While still in the proof-of-principle stage, quantum lidar [57] and radar [58] could outperform their classical counterparts in noisy or low-signal conditions [3]. Researchers at the University of Waterloo (UWaterloo) and start-up Qubic Inc. have demonstrated critical quantum radar components, including low-noise transmitters and receivers [59]. For quantum lidar, UToronto, UOttawa, and the NRC have developed correlated-photon-pair [60,61] and squeezed-light sources [62]. In combination with single-photon detectors (e.g., those from start-up Single Quantum Systems or the University of British Columbia (UBC) [63]), such sources have enabled noise-resilient target detection [64,65] and single-photon holography [66], with ongoing quantum lidar commercialization by start-up Phantom Photonics. Additionally, QVIL and start-up WaveRyde are exploring Rydberg atoms for radio-frequency electric-field monitoring in space.

Standards and metrology define and maintain accurate measurements for physical quantities, benefiting particularly from the reproducibility of atomic systems. The NRC hosts one of the world's most accurate cesium clocks [6] and novel atomic time standards are being developed by researchers at the NRC [67], UToronto [68], and QVIL. Furthermore, ultracold atoms and molecules are being leveraged for absolute pressure and particle-flux measurements at UBC and the British Columbia Institute of Technology (BCIT) [69-70]. Finally, start-up WaveRyde creates atomic vapour cells as standards for radio-frequency electromagnetic waves.

CONCLUSION

Quantum sensors are arguably the nearest-term quantum technology, with systems such as atomic clocks and SQUIDs in practical use for decades and many more on the brink of commercial adoption. Spurred by academic or government research and brought to market by start-ups, accelerators, or in collaboration with established companies, quantum sensors are finding diverse applications in sectors crucial to Canada's economy and national defence. Looking forward, as researchers and entrepreneurs refine the alignment between device capabilities and sector needs, quantum sensors are poised to drive growth and improve outcomes across a wide range of Canadian industries.

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