A Primer on Developing High-Precision Atomtronic Sensors Using Ultracold Atoms

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Abstract. This paper explores the applications of quantum atomtronics with Bose-Einstein condensates in the creation of sensors for ultraprecise measurements of gravity, rotation, and velocity. We define key principles from quantum mechanics, discuss the field of quantum atomtronics, and outline the experimental setups required for such studies. Finally, we highlight the future trajectory of this field by examining advanced research in axion detection and space experiments conducted on the International Space Station, as well as the possibility of incorporating machine learning and image recognition systems to automate the readout of atomtronic interferometers.

INTRODUCTION

A Bose-Einstein condensate (BEC) is a state of matter that occurs when a collection of bosons is cooled to near absolute zero, where a large fraction of the atoms occupy the lowest quantum state, causing them to behave as a single quantum entity with macroscopic wave function coherence. BECs allow for precise control over atomic wave functions, making them candidates for interferometry devices, and their behavior is governed by the Gross-Pitaevskii equation:

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r}) + g|\Psi(\mathbf{r},t)|^2\right]\Psi(\mathbf{r},t), \tag{1}$$

where $V(\mathbf{r})$ represents an external trapping potential and g characterizes interatomic interactions. Atomtronics is an emerging field that leverages ultracold atoms to create atomic circuits analogous to electronic systems. These systems, composed of BECs, are manipulated using optical and magnetic potentials to simulate electronic components such as resistors, capacitors, and transistors. A fundamental aspect of atomtronics is the use of optical dipole potentials to shape and control atomic wave functions. The potential energy experienced by an atom in a laser field is given by

$$U(\mathbf{r}) = -\frac{3\pi c^2}{2\omega_0^3}\left(\frac{\Gamma}{\Delta}\right)I(\mathbf{r}), \tag{2}$$

valid in the limit $|\Delta| \ll \Gamma$, where $\Delta = \omega - \omega_0$ is the detuning between the laser frequency ω and the atomic transition frequency ω_0, Γ is the natural decay rate of the excited state, and $I(\mathbf{r})$ is the position-dependent laser intensity [1]. The movement of bosons can be guided using optical potentials, as they experience attractive forces when $\Delta < 0$ and repulsive forces when $\Delta > 0$. This enables the formation of potentials through which the BEC flows, typically via a digital micromirror device (DMD), as shown in Fig. 1.

APPLICABILITY

Improved INS Devices

Inertial navigation systems (INS) are critical for modern navigation, as they enable tracking of position and orientation independently of external signals such as GPS, which are vulnerable to interference, spoofing, or unavailability. INS devices rely on integrating measurements from gyroscopes and accelerometers to estimate movement from a reference point. Gyroscopes measure angular velocity, whereas accelerometers track linear acceleration. When these measurements are integrated over time, they provide an estimate of position and attitude. However, this method, known as dead reckoning, is prone to errors that accumulate over time. As a result, INS devices require periodic recalibration using external references such as GPS signals or other high-precision measurement systems. This limitation has

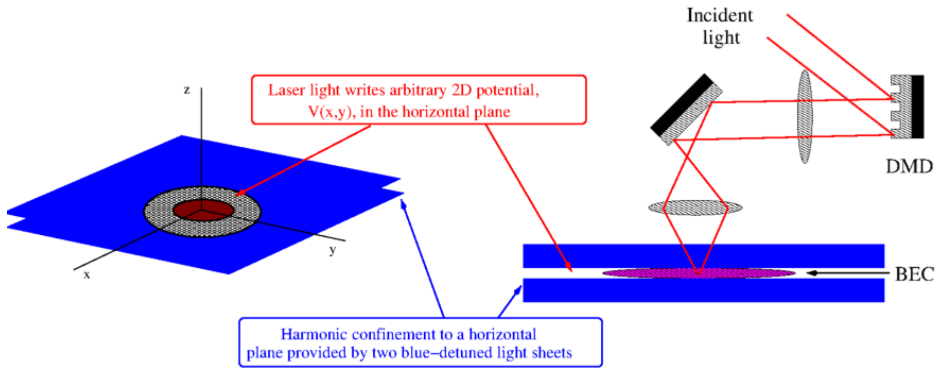

FIGURE 1. Typical experimental setup showing how DMDs control the movement of BECs within atomtronic circuits.

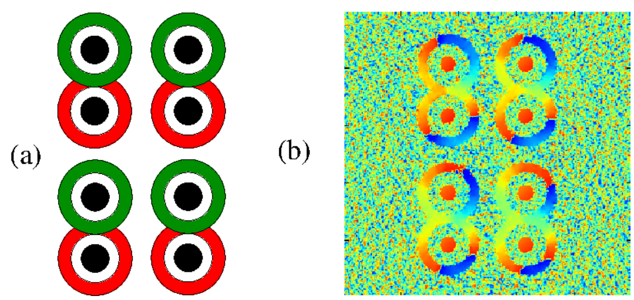

FIGURE 2. Side-by-side view for a 2×2 array where no flow transfer occurred. (a) A cartoon depiction with green representing flow and red representing no flow. (b) A phase diagram.

driven research into alternative navigation technologies, including atomtronic-based rotation sensors that leverage the coherence of BECs to provide precise and stable measurements of rotation and acceleration over long periods [2].

A proposed implementation of measuring rotation is through an array of double targets [3]. Each double target consists of two adjacent single targets, where each single target is a BEC confined to a central disk surrounded by a concentric ring. The disk serves as a stationary phase reference, while the ring supports quantized flow. Rotation is measured by inducing quantized flow in one of the rings while keeping the other ring at rest. Flow transfer between the rings is governed by the height of an applied potential barrier and the rotation speed of the frame. If the rotation speed exceeds a critical threshold, the flow will transfer between the rings, enabling precise measurements of the rotation. Simulations were performed by varying the barrier strengths across numerous double targets. The phase imprints created by flow transfer could be read from a single density or phase image (see Fig. 2), enabling the determination of which targets had transferred their flow at a glance. The experiment can be repeated with adjusted bounds for higher-accuracy measurements.

Precise Gravimetry

Scientists have conducted experiments using BECs to develop an atomic trampoline that allowed precise measurements of gravitational acceleration [4]. These experiments rely on *Bragg scattering*, a process in which atoms coherently absorb and emit photons, allowing momentum to be transferred without disturbing the overall quantum state. In the first-order process, this momentum transfer is given by $\Delta p = 2\hbar k$, where k is the wave number of the laser light used in the reflected pulses.

The experiment began with approximately 10,000 rubidium-87 atoms magnetically trapped in a tiny BEC state, ensuring that all atoms shared a single quantum wave function. After allowing the atoms to fall freely under gravity, a pulse of laser light was directed upward through the chamber. The interaction between the pulse and its reflection created standing waves, where the crests and troughs of the electromagnetic field formed a stationary pattern. When timed precisely, the downward momentum of the falling atoms matched that of the upward-moving photons. As a result, atoms absorbed an upward-moving photon and rapidly emitted a downward-moving one, effectively reversing their motion. This "bounce" was enabled by coherent Bragg scattering, facilitating efficient momentum transfer.

By adjusting the timing of these laser pulses, researchers sustained the atoms' bouncing motion for about 125 ms. The duration of a complete up-and-down cycle was measured, allowing for the calculation of g, the acceleration due to gravity. Initially, their measurements deviated by about 5% from the expected value, mainly due to the influence of Earth's magnetic field. After correcting for this effect, the refined estimate of g reached an accuracy of 0.04%.

To further enhance precision, a modified sequence of laser pulses created a two-part quantum state, allowing atoms to follow two distinct trajectories simultaneously. In one path, atoms bounced as before. In the second, lower trajectory, atoms alternated between bouncing off a virtual floor and ceiling, resulting in a higher average velocity and a shorter de Broglie wavelength. By recombining these quantum states, scientists analyzed the phase differences between their wave functions, revealing minute variations in their trajectories and speeds. The final measured value of gravitational acceleration was $g = 9.814 \pm 0.008$ m/s^2.

FUTURE DIRECTION

Ultracold Atom Experiments in Space

The future of quantum atomtronics and its applications in ultraprecision measurements holds immense promise. Ongoing experiments with NASA's Cold Atom Lab on board the International Space Station aim to improve the precision of gravimetry measurements in space. Conducting these experiments in a microgravity environment allows for a more controlled setting where external interferences, including those from Earth's magnetic field, can be minimized. This will enable the measurement of g with unprecedented accuracy, further refining our understanding of fundamental forces and improving technologies such as quantum sensors [5].

Dark Matter Detection

In addition to gravitational measurements, there is a growing interest in using quantum systems to probe dark matter, particularly in the search for axions. Axions are hypothetical particles that could be a major component of dark matter, and recent advances in quantum computing platforms have opened new avenues for their detection. For instance, by leveraging superconducting qubits—similar to those used in quantum computers—it may be possible to detect the single-photon signals that result from axion interactions with magnetic fields. These qubits are sensitive to very small fluctuations in the quantum vacuum, which could be influenced by axions, offering a unique method for dark matter detection. The use of non-Gaussian probe states may further enhance the sensitivity of these systems, allowing for faster detection times and more accurate measurements of axion-induced phenomena. Furthermore, the field of axion detection is being pushed forward by novel experimental techniques such as the Sikivie haloscope, which searches for axions by tuning a resonant cavity to match the dark matter wave's frequency. As these experiments evolve, quantum devices such as transmon qubits, embedded in superconducting circuits, are becoming key players in capturing axion-induced photon emissions. Measurement of small shifts in the qubit frequencies induced by these photons can help researchers understand the properties of axions and dark matter [6].

Machine Learning to Optimize Readouts

A significant advancement on the horizon involves automating the reading of the density profiles in BECs (shown in Fig. 3). Convolutional neural networks (CNNs) can be trained to detect and classify the density distributions of BECs from high-resolution images, eliminating the need for time-intensive manual analysis [7]. However, the impact of CNNs goes beyond just the analysis of individual experimental outcomes. The real power lies in their ability to optimize the experimental process through automation and feedback loops. For example, in the case of an atomtronic rotation sensor in Fig. 2, the density profile readouts could be used to assess the precise rotation rate and the corresponding flow transfer across BEC rings. Using CNNs to analyze these profiles rapidly allows for automated repetition of experiments, where the experimental conditions are refined after each iteration. Based on the initial

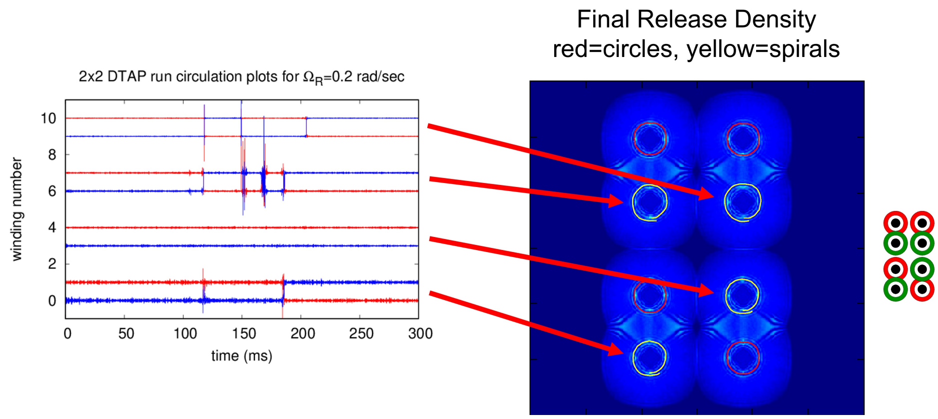

FIGURE 3. A sample density profile that can be processed automatically with CNNs.

readout, the system can adjust parameters such as barrier strength, timing, and laser pulse sequences, automatically narrowing the bounds for more accurate measurements.

CONCLUSION

In this primer, we explored the cutting-edge field of quantum atomtronics and its potential for creating ultraprecise sensors using BECs. Researchers are able to use the unique properties of BECs and atomtronic circuits to develop next-generation devices that promise exceptional accuracy in measuring physical quantities such as gravity, rotation, and velocity. Advanced experimentation in atomtronics is being conducted in space and axion detection, and the incorporation of machine learning will help automate readouts and iteratively refine experimental conditions.

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