A quantum-classical cold atom system for inertial navigation

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ABSTRACT

A cold atom system for an inertial navigation system (INS) demonstrator utilising atom interferometry is presented. Laser-cooled rubidium-87 atoms in a grating magneto-optical trap (gMOT) are used to measure acceleration along a single axis. This system demonstrates a novel technique in quantum-enabled navigation which could offer significant improvement in precision and reduction in the drift present in classical INSs. Ruggedised lasers and control electronics allow potential deployment in maritime navigation in global navigation satellite system (GNSS) denied environments. Considerations are made towards a pathway for modular expansion and development of the system to 6-axis operation.

Keywords: Atom interferometry, Quantum navigation, INS, PNT, Photonics, Optics, Laser cooling, Quantum sensors

1. INTRODUCTION

Global positioning and navigation using satellites has been a crucial part of modern infrastructure since the development of GPS during the 1970s.[1] This network of satellites has achieved a positioning uncertainty of 3 to 5 meters,[2] which has revolutionised navigation and enhanced transport across industrial, civilian and military sectors. Despite its extraordinary success, there remains an important practical need for precision navigation that does not rely on communication with a satellite. The signal from GPS is weak on earth,[3] and cannot be accessed underground or underwater for instance, making it unsuitable for applications in these environments. Additionally, it can be easily spoofed or disabled at relatively low cost.[4] The development of navigation systems that can operate in these conditions is essential for the operation of maritime vehicles in these environments.

Current micro-electro-mechanical system (MEMS) based classical inertial navigation systems allow for good precision for navigation,[5] however there is an inherent bias drift in these systems that lead to large uncertainties in position.[6] A quantum sensor based on atom interferometry doesn't experience this systematic drift and can be used as a drift-free navigation accelerometer. The inherent downside of using quantum sensors this way is their low bandwidth and low repetition rate. This can be overcome by using a hybrid quantum-classical INS. This system would use a quantum sensor to condition the classical one, removing the drift and reducing positional uncertainty in the classical INS. A step towards realising this is to develop an INS with a quantum accelerometer operating in one axis, that conditions a single axis of a classical INS with the eventual goal of having a 6-axis quantum-classical system.

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2. PHYSICS PACKAGE

The accelerometer used as the quantum sensor is a Mach-Zehnder style atom interferometer using rubidium-87 atoms cooled and trapped using a grating. The advantage of the grating is that it requires only one input cooling beam, reducing the size of the system compared to conventional 3D MOT trapping geometries. The 0th and 1st order reflected and diffracted modes of the grating form the trapping potential required to form the magneto-optical trap. The vacuum package was built by TMD[7] and is a compact, with dimensions of 25.0 x 4.0 x 3.2 cm^3 and a mass of 252 g and has an integrated gMOT.[8] A pair of anti-Helmholtz coils form the position-dependent magnetic field gradients required for trapping. An example of the vacuum system can be seen in fig.1

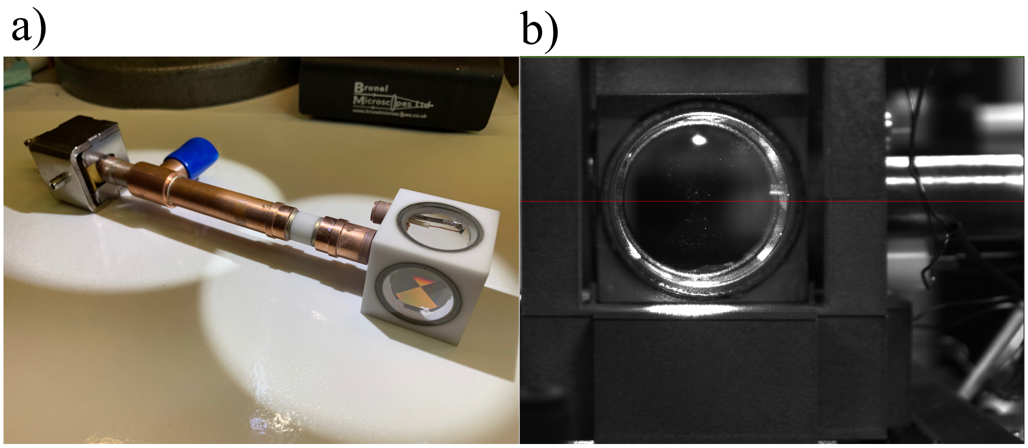

Figure 1. Components of the vacuum system used as the physics package for the quantum accelerometer. Image a) shows a demonstrator model, similar to the vacuum system used in the accelerometer and b) is an image of atoms captured in the MOT.

Active external magnetic field compensation is provided by three sets of orthogonal shim coils in a Helmholtz configuration. Additional magnetic shielding is provided by a two-layer mu-metal shield that surrounds the vacuum chamber and coils.

The cooling laser is delivered from beneath the physics package; a polarisation-maintaining (PM) fibre delivers light to the beam expansion optics. A circular polariser is used to ensure the correct polarisation for cooling and trapping. There are windows for Raman beams and retro-reflection optics with another separate window for detection. The interferometry sequence used in this system is displayed in fig.2

The counter-propagating, circularly polarised Raman beams are delivered through a single optical fibre, with the polarisations of the beams coupled to the slow and fast axes of the fibre respectively. A quarter-wave plate (QWP) built into the collimator converts the linear polarisations to circular. On the retro-reflection arm of the physics package there is another QWP and a polarising beamsplitter (PBS) that dumps one of the polarisations. The resulting Raman system is overlapped circular polarised light of the same handedness from the perspective of the atoms. In order to reduce the laser phase noise in the system, the retro-reflection side of the Raman system features a single-axis MEMS accelerometer fixed to the mirror. The accelerometer tracks the vibrations of the mirror so that they can be characterised and mitigated for when measuring the phase of the interferometer.

Detection is done using a confocal imaging system to focus light from the fluorescing atoms onto a photodetector and reducing the effects of scattered light. There is a camera on the retro-reflection arm that can also be used to image the atoms in the MOT. This camera can be used for diagnostics, to measure the temperature of the atoms using the time-of-flight (TOF) technique. It also can be used to look at the profile of the Raman beams.

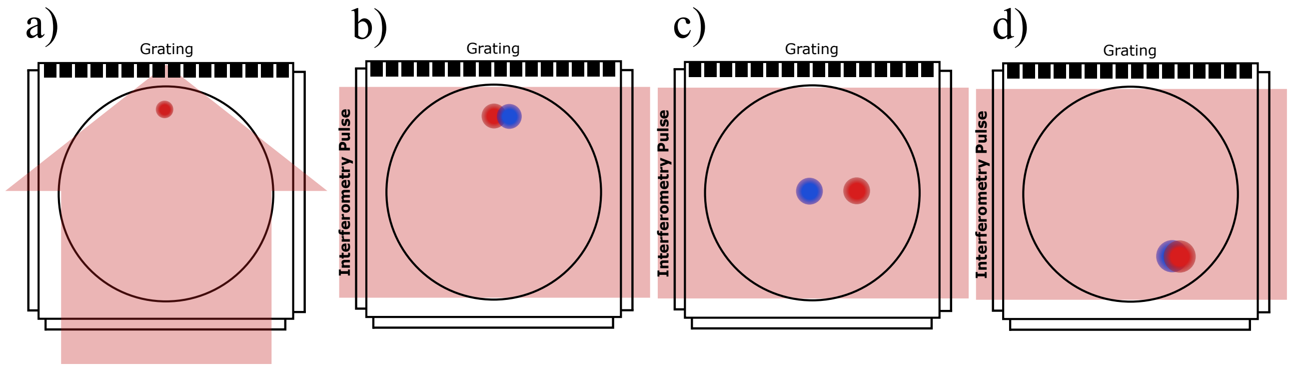

Figure 2. Simple diagram of the interferometry scheme for the accelerometer. Cooling and trapping by a single input laser beam incient on the grating is shown in a). Retro-reflected, counter-propagating Raman beams apply a pulse acting as a beamsplitter in b). A mirror puls is applied, inverting the state populations of the rubidium atoms in c). Finally, d) shows a second beamsplitter pulse recombining the atoms. The relative state populations are then measured.

3. SYSTEM DIAGNOSTICS AND PERFORMANCE

The vacuum system loads $> 10^6$ atoms in the MOT with a load rate of $> 10^6$ atoms per second. The atoms are further cooled using polarisation gradient cooling to < 15 μK. A TOF measurement can be seen in fig.3.

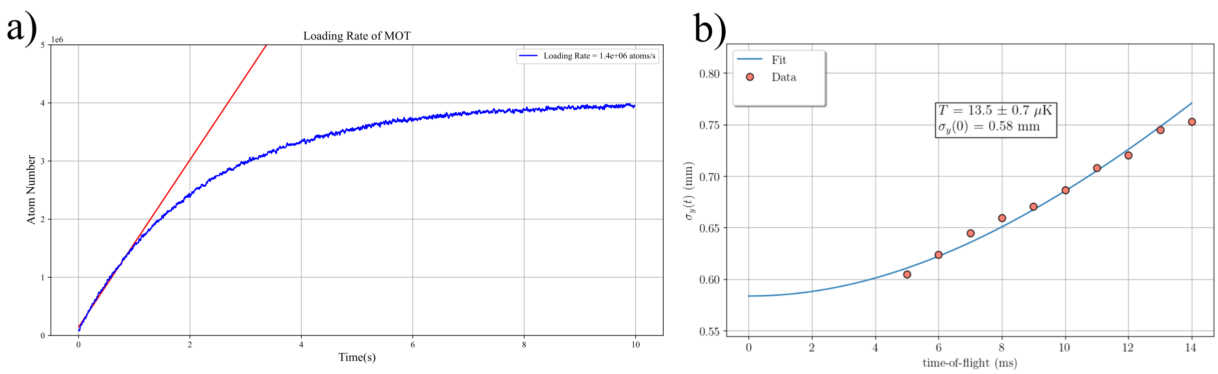

Figure 3. The loading curve of the MOT is can be seen in a) with the loading rate extrapolated from the first second of load time. The load rate is higly dependent on the rubidium pressure with an order of magnitude faster loading possible at higher rubidium pressure. The temperature of the atoms is extracted in a time-of-flight measurement shown in b).

The energy states of the atoms have been manipulated using microwaves. The atoms are allowed to fall to the F=1 state by turning off the repumper at the end of the sub-Doppler cooling sequence. A microwave pulse has been used to scan over the F=1 to F=2 transition. Rabi oscillations have also been observed using this frequency and by varying the pulse length. These can be seen in fig.4.

These scans demonstrate manipulation of energy levels but not momentum transfer making these unsuitable for acceleration measurements. In order to utilise this system as an accelerometer for inertial navigation, counter-propagating Raman beams are required.

4. OUTLOOK AND DYNAMIC SYSTEM TESTING

Since this is a hybrid quantum-classical INS, how the quantum sensor conditions the classical sensor is important to quantify. To this end a test rig is currently being constructed to move the physics package in a controlled way so that the system can be tested dynamically. The test rig consists of two high-torque rotational motors, allowing measurements to be taken over a range of angles relative to gravity to see how the system will perform

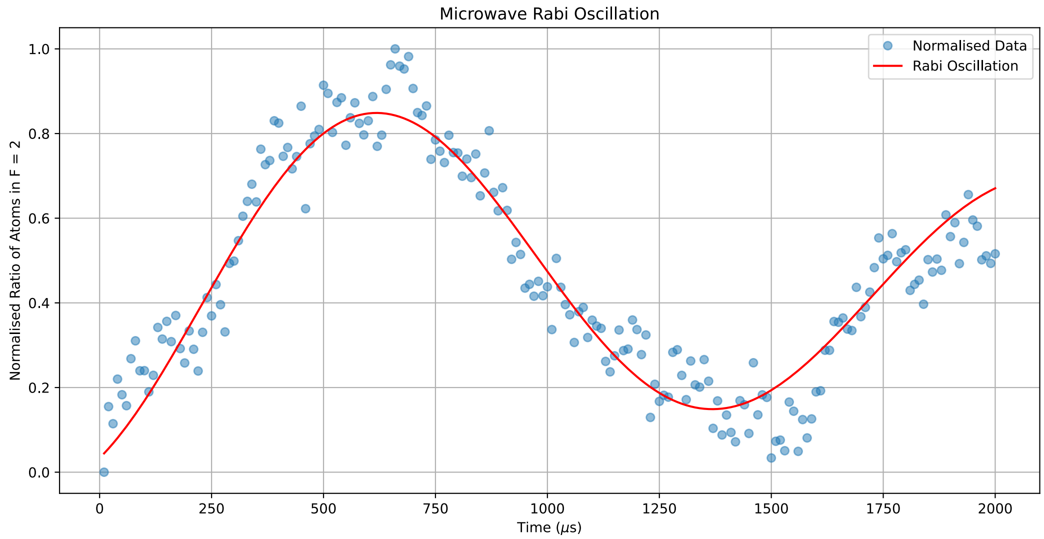

Figure 4. Rabi oscillation measurement using a patch antenna installed inside the vacuum package. Using these microwave parameters a π pulse has a length of 625 μs. The use of the patch antenna allows for state selection using microwaves.

when used in a dynamic environment. This will also allow the tuning of Raman beam frequency to compensate for Doppler shifts when falling at different relative angles to gravity.

In addition to in-house testing by controlled rotation, the system will also be tested in an active environment. This will take the form of a maritime trial of the final system. The system will be subject to a week long sea trial to evaluate the performance of the sensor as well as other practical limitations of running the accelerometer in a maritime environment. The results from this test will be used to upgrade the system where necessary for a repeat test run six months after the initial sea trial. Further upgrades will also be made to the system such as integrating a 2D MOT to increase loading rate and atom number.

The eventual goal of the project is to produce a complete quantum-classical six-axis inertial navigation system consisting of sensors in the cardinal directions and three quantum gyroscopes for rotational measurements. Due to the limitations in bandwidth and repetition rate inherent in these quantum sensors, they will continue to be used to condition classical sensors in this approach. A fully quantum system using atom interferometry as an accelerometer will likely not be viable in the short-term future, so this approach is the most practical for realising a low-drift, high-precision INS.

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