Bury, A, Khalique, A and Kaminski, K

Quantum navigation: The future beyond Global Navigation Satellite Systems

Quantum navigation

The future beyond Global Navigation Satellite Systems

Dr Alan Bury MNM
Liverpool John Moores University

Abdul Khalique
Liverpool John Moores University

Kamil Kaminski
Liverpool John Moores University

In an era where Global Navigation Satellite Systems (GNSS) underpin the world's transportation, logistics, communication, agriculture, financial services, emergency response, and defence networks – to name just a few – their pervasiveness has created a critical dependency. While GNSS have revolutionised Positioning, Navigation and Timing (PNT) services, offering unparalleled convenience and global coverage, their inherent limitations and vulnerabilities pose significant risks to critical infrastructure and national security.

A groundbreaking technology has emerged as a potential solution. By making use of the quantum properties of ultra-cold atoms, atom interferometry is posed to provide an inertial navigation solution to GNSS dependence. This technology offers the prospect of a self-contained navigation system that does not rely on external signals, and does not require frequent recalibration like other inertial navigation systems, addressing the urgent need for alternatives to mitigate GNSS vulnerabilities. While the technology is not yet at a stage where it can be installed on ships as standard, the pace of development means that this is a strong possibility for the future.

Why go beyond GNSS?

As our reliance on GNSS – consisting of GPS (United States), GLONASS (Russia), BeiDou (China), and Galileo (European Union) – deepens, the limitations of these systems have become increasingly apparent. One of the most significant technical constraints lies in the requirement for a clear line of sight to orbiting satellites. This fundamental requirement renders GNSS signals unavailable or unreliable in many environments. Urban areas with tall buildings create 'urban canyons', where signals are either reflected or blocked entirely, leading to degraded positioning accuracy. Underwater environments present another limitation, since radio waves cannot travel through water beyond shallow depths. These technical constraints make GNSS unsuitable for many specialised applications that require precise navigation in challenging environments, highlighting the need for alternative navigation technologies.

Even when a signal is available, they are susceptible to degradation caused by environmental factors. Atmospheric disturbances in the ionosphere and troposphere can delay or distort signals, reducing their accuracy. Additionally, solar activity such as flares can disrupt satellite communications, creating temporary outages that affect navigation systems reliant on GNSS.

Beyond these natural limitations, there is a significant risk from deliberate interference. Signal jamming is one of the most common forms of disruption, where stronger signals transmitted on the same frequency overpower legitimate GNSS signals. Signal jammers, although illegal, are inexpensive and widely available, making them a growing concern for industries dependent on uninterrupted navigation services. Spoofing presents an even more insidious threat. By transmitting counterfeit GNSS signals, malicious actors can deceive receivers into reporting false positions. Unlike signal jamming, which causes an immediate loss of signal, spoofing can subtly manipulate navigation data without raising alarms. This makes it particularly dangerous for critical systems such as those used for navigation. The economic implications of such disruptions are substantial, as they can cause delays and increased operational risks, leading to significant financial losses in the aviation and maritime sectors, where precise navigation is crucial for safe and efficient operations. A single day of GNSS outage could result in multimillion dollar losses in addition to lost user confidence in these systems.

The vulnerabilities of GNSS extend beyond technical challenges to include geopolitical risks. The four major GNSS constellations are controlled by nation-states or regional entities.

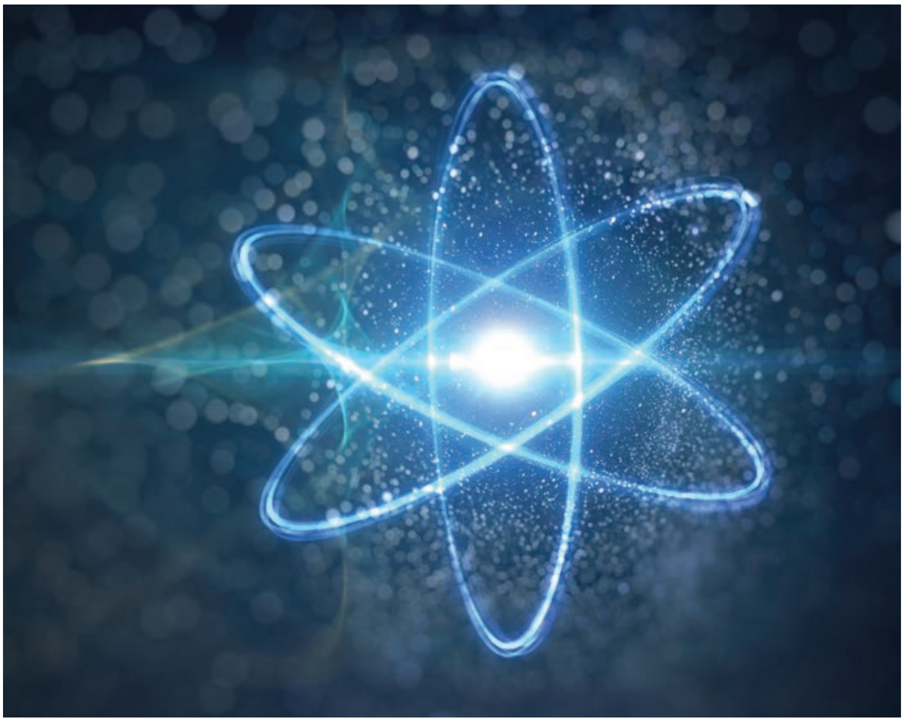
The science behind atom interferometry

At the heart of atom interferometry lies the fascinating realm of quantum mechanics. This cutting-edge technology takes advantage of the dual nature of matter, where atoms exhibit both particle-like and wave-like behaviour. While this concept might seem abstract, it is a cornerstone of modern physics and the key to understanding how atom interferometry works.

Atom interferometry is a key technology in quantum inertial navigation systems (Q-INS), enabling ultra-precise measurements of acceleration and rotation without relying on an external signal. To understand atom interferometry, it helps to imagine atoms as tiny waves moving through space. Under normal conditions, these atomic waves are chaotic and difficult to manipulate. However, by cooling the atoms to temperatures close to absolute zero, they can be slowed down and their movements brought under control. Once cooled, the atoms are effectively 'trapped' in a specific location using electromagnetic fields. This creates a stable cloud of ultra-cold atoms that can be precisely manipulated with laser pulses. These pulses serve multiple purposes. Firstly they split each atomic wave into two separate paths. In this state, each atom exists simultaneously in two different locations - an idea that might sound like science fiction but is a well-documented phenomenon in quantum mechanics known as superposition. Next, they guide the atomic waves along different trajectories. As these atomic waves travel along their respective paths, they encounter external forces that cause subtle changes in each wave. Finally, the laser recombines the waves and, in doing so, creates an interference pattern 'fingerprint' that encodes information about the forces experienced along each path. By analysing this 'fingerprint', highly accurate measurements of acceleration, rotation, or gravitational forces can be calculated.

The extraordinary sensitivity of this process allows for exceptional accuracy in detecting even minute changes in motion or force. By harnessing such atomic-scale quantum phenomena, an atom interferometer can calculate movement and provide navigation information to a degree of accuracy far surpassing today's commercially available navigation systems.

A representation of a quantum waveform



While these systems are increasingly interoperable and accessible globally, they remain subject to the political agendas of their operators. In times of geopolitical tension or conflict, access to GNSS services could be restricted or denied altogether. For example, a nation could selectively degrade or block its signal in specific regions to gain a strategic advantage during military operations. This creates a critical dependency on foreign-controlled infrastructure that could be exploited in ways that disrupt global trade, transportation networks, and defence systems.

Inertial Measurement Units (IMU)

Inertial Navigation Systems (INS) have long been used as a backup for GNSS, providing crucial navigation data when satellite signals are unavailable or unreliable. At the heart of these systems are Inertial Measurement Units (IMU), which rely on accelerometers and gyroscopes to track movement and orientation. Accelerometers measure linear acceleration along different axes, while gyroscopes detect rotational motion. By integrating data from these sensors over time, an INS can calculate changes in velocity and position relative to a known starting point. This improved dead reckoning approach allows vehicles, aircraft, and ships to navigate without external references, making it invaluable for applications where GNSS might be compromised or unavailable.

However, traditional INS suffer from a significant drawback: drift. Small errors in acceleration and rotation measurements, which are inherent in mechanical sensors, accumulate over time. This accumulation leads to increasingly significant positioning errors as a journey progresses. For example, a navigation grade IMU, when operating unaided (without external correcting input) could expect to drift by up to one nautical mile per hour. This is obviously problematic for journeys of long duration. As a result, traditional IMUs often require periodic recalibration using external references like GNSS to maintain accuracy.

This is where atom interferometry enters the picture, offering a quantum-based solution to the limitations of traditional IMU. An atom interferometer functions as a highly sensitive, quantum mechanics-based IMU. Unlike traditional sensors that rely on mechanical components, atom interferometers use quantum phenomena that remain stable and consistent over extended periods without external reference, maintaining a level of accuracy that far surpasses current commercially available navigation systems.

As with other INS, the independence of atom interferometry from external infrastructure makes it immune to the jamming and spoofing attacks that plague GNSS-dependent systems. By operating as a standalone system capable of measuring acceleration and rotation with extraordinary precision, atom interferometers can provide reliable navigation data even in environments where GNSS is unavailable or compromised. The enhanced accuracy and stability of atom interferometry-based navigation systems could revolutionise industries that are reliant on precise positioning and timing.

Applications of atom interferometry

In the maritime sector, atom interferometry enhances operational capabilities across different vessel types. Ships operating in open oceans often rely heavily on GNSS for positioning. In areas where signals are unreliable or unavailable – such as near dense coastal structures or during intentional jamming events – atom interferometry could step in to provide precise navigation data.

The technology is equally transformational for vessels navigating through challenging environments, such as research vessels conducting scientific missions in polar regions. At high latitudes GNSS coverage is often poor due to the low elevation angles of satellites, leading to reduced accuracy and potential signal loss. Atom interferometry could provide a robust navigation system that is reliable regardless of a vessel's position on the surface of the Earth. Cargo ships traversing busy shipping lanes could benefit from the technology's resistance to jamming and spoofing, ensuring safe and efficient passage even in contested or high-risk waters.

Submarines and Autonomous Underwater Vehicles (AUVs) both currently rely on acoustic positioning systems or INS that accumulate errors over time, requiring periodic surfacing to recalibrate their position using GNSS. With atom interferometers, submarines could maintain accurate positioning for extended periods without surfacing, enhancing their stealth and operational capabilities. Similarly, equipping AUVs with atom interferometers would enable them to navigate independently over longer distances with greater precision, potentially revolutionising ocean exploration and underwater research.

Current uses

The aviation industry is integrating atom interferometry into its systems to enhance flight safety. In May 2024, the UK government successfully tested a quantum inertial navigation system (Q-INS) on a commercial aircraft, demonstrating satellite-independent tracking. These trials demonstrated that Q-INS could successfully track an aircraft's position and orientation without any input from satellites – a ground breaking achievement that paves the way for widespread deployment of this technology in aviation. By 2030 – as outlined in the UK's National Quantum Strategy – Q-INS could become standard in commercial aircraft, providing an additional layer of navigation reliability.

Advances in atom interferometry technological

While the underlying principles of atom interferometry build on decades of research into quantum mechanics and atomic physics, recent technological advances have driven remarkable progress in the field. These developments are reconfiguring atom interferometers from bulky laboratory set-ups into compact, field-deployable devices with practical real-world applications.

One of the most significant breakthroughs has been miniaturisation. Traditionally, atom interferometers required large, complex set-ups that filled an entire laboratory. However, recent advances have dramatically reduced their size. For example, the University of Michigan has developed a quantum rotation sensor with a core smaller than the width of a human hair. The miniaturisation process has also benefited from several other technological advances.

Lithographic techniques similar to those used in the manufacture of computer chips have been utilised to produce miniature magnetic traps for atoms. These allow for precise control of atomic clouds in a fraction of the space required by traditional set-ups.

Recent developments in micro-electromechanical systems (MEMS) have led to the creation of chip-scale vacuum pumps and chambers. These miniature systems maintain the necessary ultra-high vacuum conditions for atom interferometry while significantly reducing the overall size of the device.

The development of compact, stable, and tuneable diode lasers has also been instrumental in reducing the size of atom interferometers. Moreover, advances in fibre optic technology and integrated photonic components have allowed for more efficient delivery of laser light, further contributing to size reduction and improved performance.

Alongside miniaturisation efforts, researchers have made significant strides in improving the stability and robustness of atom interferometers. Modern designs are increasingly resilient to environmental noise such as vibrations and temperature fluctuations. This enhanced robustness is crucial for deploying these devices in real-world settings where conditions are far from the controlled environment of a laboratory.

Another significant area of advance is in the integration of atom interferometers with other quantum technologies, such as quantum memories or quantum communication systems. By combining atom interferometers with atomic clocks, researchers have created systems with unprecedented timing precision. This synergy has opened new possibilities for ultra-precise positioning and navigation, significantly boosting the overall accuracy of systems that make use of them.

The development of more efficient atom sources has also been a key area of research. Increasing the intensity of atom sources helps reduce uncertainty caused by the limited number of atoms used in the process. This provides a more coherent and controllable input for atom interferometers, enhancing their overall sensitivity and accuracy.

Advances in data processing and control systems have also played a crucial role. The development of sophisticated algorithms and real-

Quantum navigation tests being carried out on the Avro RJ100
Colin Cook Photo - Creative Commons

time feedback systems has improved the ability to extract meaningful information from atom interferometer outputs. Machine learning techniques are also being applied to analyse interference patterns, enabling more accurate and rapid interpretation of results.

The quest for room-temperature atom interferometers represents another frontier in the field. While most current systems rely on ultra-cold atoms, operating at temperatures near absolute zero, researchers are exploring ways to create interferometers that can function at or near room temperature. Success in this area could dramatically simplify the design and operation of the technology, making it more suitable for widespread deployment.


Quantum navigation could also revolutionise space exploration

Challenges to be addressed

Despite the significant progress in atom interferometry, several challenges must be addressed to enable widespread adoption. These challenges span economic, technical, and practical domains.

Atom interferometers are currently expensive due to the complexity of quantum systems and specialised equipment. High-precision lasers, ultra-high vacuum systems, and sophisticated control electronics all contribute to a substantial per-unit cost. A single, laboratory-grade atom interferometer can cost several million dollars, making it prohibitively expensive for many potential applications. Researchers are exploring hybrid systems that combine quantum sensors with classical inertial navigation technologies to reduce costs without compromising performance.

While impressive results have been achieved in laboratory settings, transitioning from laboratory prototypes to mass-produced commercial devices requires engineering advances to be made to maintain sensitivity while adapting for large-scale production. Efforts include developing compact, ruggedised systems with fixed optical components and custom vacuum packages, such as the golf-ball sized vacuum chamber being developed at Sandia National Laboratories which could significantly reduce the overall size and complexity of these devices.

Maintaining long-term stability in smaller devices, especially during extended missions, remains a significant challenge. To address this, scientists are pursuing multiple strategies. They are developing better methods for controlling and isolating atomic systems from unwanted external disruptions, such as vibrations. Additionally, they are improving laser systems to achieve greater stability and reduce the noise they produce. All of these improvements are critical, as both external disturbances and laser noise reduce the accuracy of measurements. These efforts are complemented by the development of advanced error correction algorithms and real-time calibration techniques.

Atom interferometers can struggle with large or rapid movements, such as might be encountered in aircraft. Researchers are investigating combining atom interferometers with conventional sensors and adaptive measurement schemes that can adjust the sensitivity of the equipment in real time based on the current motion conditions.

External factors like magnetic fields, temperature fluctuations, and vibrations affect atom interferometers. Making them robust for all environments is crucial, particularly for applications in harsh conditions.

A new paradigm in navigation

Atom interferometry represents not just an incremental improvement in navigation technology but a fundamental paradigm shift. This groundbreaking technology promises to revolutionise not only how we navigate our world but also how we explore the fundamental nature of the universe itself.

The journey from laboratory curiosity to practical, widely deployed technology is well under way. As researchers continue to overcome challenges and push the boundaries of what is possible, we can anticipate a future where quantum precision becomes an integral part of our technological landscape.

In the coming years, we can expect atom interferometry to play an increasingly crucial role across various industries and scientific disciplines. As we embrace this quantum revolution, we are reminded that every great journey begins with a single step – or in this case, a single atom.