A Quantum Leap for Navigation

Allison Kealy FRIN (Swinburne University of Technology) and Andrew Greentree *(RMIT University of Technology)* explain what quantum navigation is, where we are now and the challenges and opportunities that lie ahead.

The United Nations has declared 2025 the International Year of Quantum Science and Technology (IYQ) (UNESCO, n.d.). This milestone marks a century since Heisenberg, Born, and Jordan laid the foundations of matrix mechanics and Schrödinger introduced wave mechanics, two cornerstones of quantum physics, i.e. the science of how tiny particles like atoms behave. This work laid the foundation for many modern technologies, including semiconductors, lasers, quantum computers and now quantum navigation.

At the quantum level, the particles that make up everyday objects, such as electrons and atoms, behave in ways that defy our classical understanding of the world. Two key quantum phenomena that illustrate this are superposition and entanglement. Superposition is when quantum particles exist in multiple states at the same time. Imagine tossing a coin: in the classical world, the coin is either heads or tails while in the air, and we only know the result once it lands. However, in the quantum world, the coin can be both heads and tails simultaneously until measured. Entanglement occurs when two or more particles become linked so that the state of one instantly affects the state of the other, no matter how far apart they are. Think of tossing two coins at the same time—if they are entangled, knowing the outcome of one (e.g., heads) immediately determines the outcome of the other (e.g., tails), even if they are separated by vast distances.

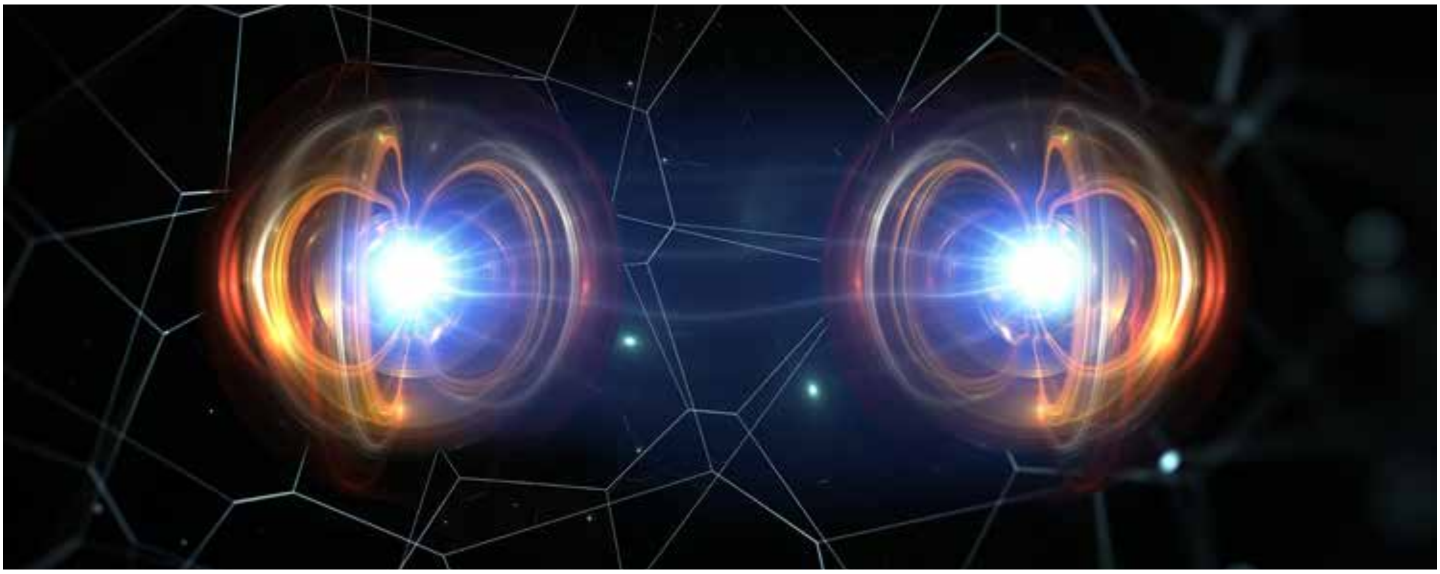
These concepts challenge our traditional view of reality—after all, in the classical world, a coin cannot be in two states at once or be inherently linked to another coin in this way. Yet, superposition and entanglement form the foundation of the new quantum technologies. They enable quantum sensors to probe their environment with unprecedented precision and drive advancements in secure communication, computing, and ultra-precise Positioning, Navigation, and Timing (PNT) systems.

From autonomous vehicles to space exploration, quantum navigation offers unparalleled capabilities in environments where conventional systems fall short. In this article, we'll explore what quantum navigation is, how it works, where we currently stand, and where it's headed.

Next Generation Navigation Sensors?

Quantum sensors, built on the fundamental laws of quantum mechanics, provide the most precise measurements possible for their size, offering a significant leap forward in sensor technology. For navigation, this translates into new ways to measure position and motion with unparalleled accuracy. As quantum sensors are based on the properties of particles such as atoms or photons, and because the fundamental properties of particles don't change, sensors based on these properties are inherently bias-free, which makes them less prone to errors due to drift that often affect traditional sensor systems.

Today, navigation systems such as GNSS (Global Navigation Satellite Systems), are essential for positioning and tracking, supporting services ranging from everyday smartphone applications to military operations. There are, however, some environments where GNSS simply does not work, or where its susceptibility to jamming and spoofing raises security concerns, for example, inside tunnels, urban environments, underwater, or in certain military operations, where secure, uninterrupted navigation is crucial. To address these limitations, classical sensors, such as accelerometers and gyroscopes (inertial sensors), are often used to augment GNSS and provide navigation solutions when the GNSS signal is unavailable. However, these inertial sensors tend to drift over time, which reduces their accuracy and operational effectiveness without the periodic availability of an external reference signal from GNSS. Additionally, the size, weight, power, and cost (SWAP-C) limitations of classical inertial sensors make them impractical for some applications that could otherwise benefit from accurate and continuous navigation. While inertial sensors are invaluable in many contexts, today, for many applications, they cannot fully replace GNSS or operate independently due to these constraints.



Quantum sensors (accelerometers, gyroscopes, gravimeters, and magnetometers) offer promising solutions to these challenges. These sensors rely on advanced quantum techniques to enable highly precise measurements in GNSS-denied environments. Each technique offers distinct advantages for different types of navigation systems, examples include:

Cold atom interferometry uses ultra-cold atomic clouds, or exotic quantum states such as Bose-Einstein condensates or atom lasers and manipulates their wave-like properties to measure changes in acceleration or velocity – the quantum inertial measurement unit (IMU). This allows quantum accelerometers and gyroscopes to measure motion with extreme precision, enabling navigation without external signals like GNSS. These sensors are ideal for applications such as submarines, spacecraft, and autonomous vehicles, where traditional systems may struggle to provide long-term navigation.

Nitrogen vacancy (NV) centres are an atom-like defect in a diamond lattice. NV centres respond to magnetic fields with remarkable accuracy and optical readout of their quantum state at room temperature. This capability makes NV-based sensors highly effective in measuring the Earth's magnetic field, providing an alternative to traditional navigation methods.

Optically pumped magnetometers, or vapour cells, are

Quantum Technique	Advantages	Disadvantages	Sensitivity Modality
Cold Atom Interferometry	Ultra-precise motion measurements - No reliance on external signals like GPS - Long-term stability	- Sensitive to environmental conditions (e.g., temperature) - Bulky and expensive - Requires precise laser manipulation	Accelerometery 11.2 μm s-^{2}/√Hz (Salducci et al. 2024) Gyroscopes 1.8 μ rad s-^{1}/√Hz (Salducci et al. 2024) Gravimetry 37 μGal/√Hz Wu et al. 2019)
Nitrogen Vacancy (NV) Centres	- High sensitivity to magnetic fields - Compact and versatile - Robust in extreme conditions	- Sensitive to temperature and calibration noise	Magnetometry 460 fT/√Hz (Barry et al. 2024)
Optically Pumped Magnetometers	- High precision in magnetic field measurements - Compact and lightweight - Commercially available	- Limited by magnetic field strength - Environmental sensitivity to temperature changes	Scalar magnetometry 20 fT/√Hz (Oelsner et al. 2019)
Superconducting Qubits	- High precision in time, position, and velocity measurements - Potential for advanced quantum navigation algorithms	- Requires extremely low temperatures (cryogenics) - Large and complex setup - Difficult to deploy on mobile platforms	fT/√Hz (CSIRO, 2024)
Entanglement-Based Sensing	- Unmatched precision in measurements - More resilient to certain types of noise	- Technically difficult to create and maintain entangled particles - Not yet deployed in practical navigation	Magnetometry 12 pT/√Hz. (Ruster at al. 2017)
Trapped Ions	- Highly accurate time measurements - Long-term stability - Well utilised for standards and precision metrology	- Requires sophisticated and large equipment - Sensitive to electric fields and temperature changes	Time, relative uncertainty 9.4 x 10-^{19} (Brewer et al. 2019)

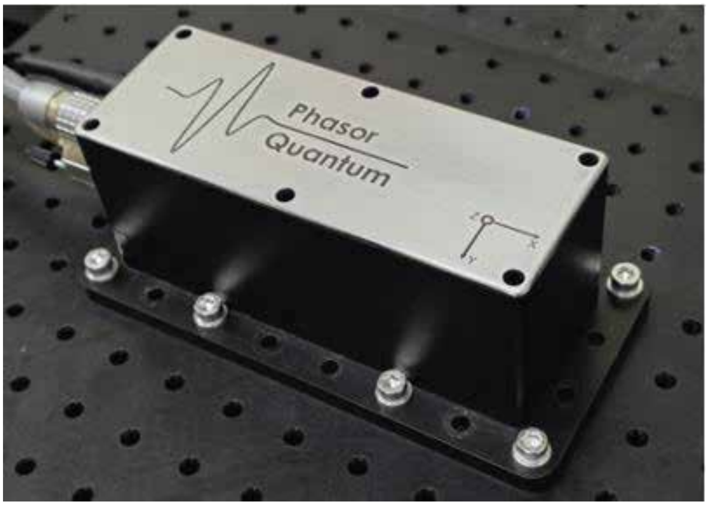
Table 1. Advantages and disadvantages of relevant advanced quantum techniques for navigation including some indicative sensitivities and modalities.

another quantum system used in quantum magnetometry. These devices are based on low-pressure gasses of rubidium. Vapour cells provide scalar magnetometry and often require compensation to work in the Earth's magnetic field. Nevertheless, they are a robust and well-developed technology that is already in commercial production.

Quantum or Classical – which is better?

Quantum navigation is still an emerging field, but decades of investment in fundamental science and precision metrology is now transforming into an exciting technology space, with start-ups and established industries rushing to exploit the potential of quantum.

Although quantum navigation systems are not yet ready for wide-scale deployment, the technology is maturing rapidly. Boeing recently announced a four-hour GNSS-free test flight, where they incorporated a six-axis quantum IMU based on atomic interferometry, with an NV diamond-based quantum magnetometer, as well as a mix of classical navigation approaches (Boeing, 2025). It is fair to say that we really don't know what the boundaries of the possible are with quantum, and we won't know until wide-scale deployment is achieved. To explore these boundaries, we have partnered with Phasor Quantum to develop a cutting-edge sensor that harnesses NV colour centres in diamond (see Figure 1). This represents the forefront of quantum magnetometry, delivering unprecedented precision and reliability. In a landmark achievement, the sensor was successfully deployed in a long-range flight trial in Australia, demonstrating its real-world viability. This collaboration marks a crucial step in transforming groundbreaking research into practical, field-ready technology.



What has become obvious in this program of work is the need to differentiate between the development of a quantum sensor for navigation and a navigation system or solution. Today's quantum sensors are unable to function without classical systems, necessitating quantum-classical fusion. In our work, we have combined a quantum magnetometer with a classical inertial sensor and map matching to create a hybrid navigation system. While quantum magnetometers provide highly precise measurements of magnetic fields, and classical inertial sensors track motion and orientation, the system then uses map matching to refine the estimated position on the basis of all of the data. This fusion of quantum and classical systems helps correct drift from the inertial sensors and ensures reliable navigation, even in challenging environments where traditional systems cannot function. Indeed, such

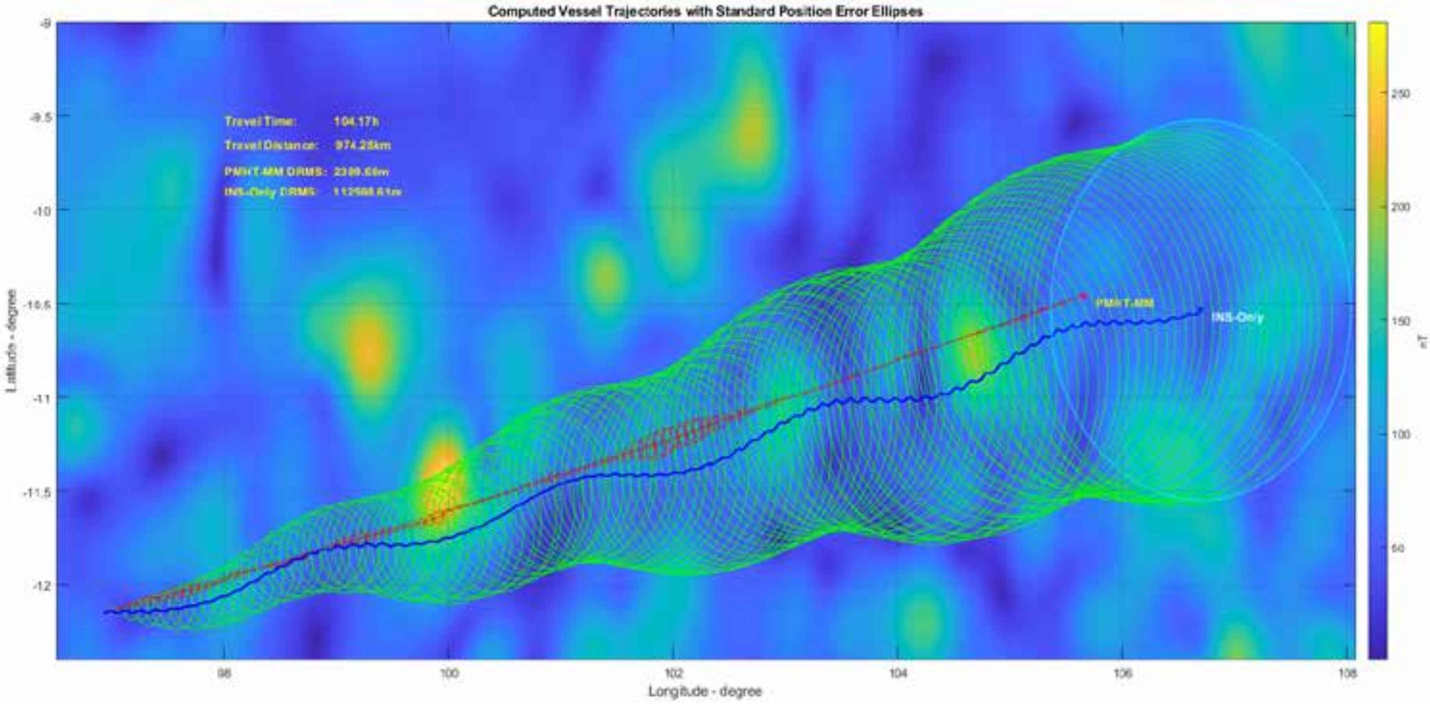


Figure 1: (Top) Portable NV magnetometer made by Phasor Quantum (image used with permission). (Bottom) Trajectory comparing navigation using inertial navigation system only (blue line with green error circles) with inertial navigation system aided by NV magnetometer with map matching (red line with red error circles). In this simulation the magnetometer aided navigation achieved almost a 50 times reduction in error over almost 1000 km trajectory and 104 hours. (Figure supplied by X. Wang, used with permission).

a hybrid approach, combining the strengths of quantum sensors with classical systems, is likely to remain in place for the foreseeable future (Salducci et al. 2024).

Challenges Facing Quantum Navigation

While the future of quantum navigation looks promising, several challenges remain:

1. Environmental Sensitivity: Quantum sensors are incredibly sensitive to their environment, which makes them exquisite sensors. However, it also means that they are vulnerable to changes in temperature, pressure, or magnetic fields that can interfere with the measurements, causing noise or errors. Researchers are working to make these sensors more stable and resilient in real-world conditions.
2. Size and Power Consumption: Traditional quantum sensors were limited to laboratories and required significant space and power, which limits their practical use in portable or mobile applications. Miniaturising quantum sensors while maintaining their performance is an ongoing challenge, with diamond and vapour cell systems showing exceptional promise.
3. Cost: The technology behind quantum sensors is still relatively expensive. While costs are expected to decrease as the technology matures, quantum navigation systems are currently out of reach for many industries, particularly in comparison to traditional GPS-based systems.
4. Integration with Classical Systems: Quantum sensors and classical systems (like GNSS and inertial navigation systems) work in fundamentally different ways. Combining the two to create a seamless hybrid navigation system that maximises the strengths of both is an ongoing challenge.

Conclusion

Quantum navigation sensors are poised to influence how we navigate the world. While still in the experimental phase, the potential applications are vast, and companies are taking the first steps towards commercialising quantum solutions. With continued research and development, quantum navigation could offer a level of performance that current systems can't match.

As quantum sensors become smaller, more efficient, and more robust, the future of navigation looks set to be both more accurate and more autonomous. As the technology develops, we can expect to see more compact, energy-efficient quantum sensors that can be easily integrated into a wide range of applications. Quantum sensors will also become more resilient, allowing them to operate in a broader range of environments.

Acknowledgements

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