Quantum Technologies in Resilient Position Navigation and Timing

Prof Kai Bongs, Roger McKinlay and George Shaw bring you the first article in the Resilience Series as introduced by John Pottle in the previous edition of Navigation News.

INTRODUCTION

Once upon a time, all navigation was natural-navigation with no dependence on equipment. Early mariners used the sun by day, the stars at night and a map lodged in the memory of an experienced master mariner.

In time navigators acquired tools: a magnetic compass; instruments for measuring angles; and – famously - robust and accurate clocks. The new navigator - although weighed down with a few instruments, remained largely self-reliant.

RADIONAVIGATION

The invention of radio brought new tools in the form of direction finding systems and hyperbolic navigation systems such as LORAN. However, the technology was limited in both reliability and range.

GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

The building of the Global Positioning System constellation in the 1980s changed everything. A space-based radio navigation system provided high quality position, navigation and timing to everyone, everywhere, for free. The self-reliant navigator became redundant.

Or maybe not. If Global Satellite Navigation Systems excel in being super-accurate and always available, they excel more so in being deceptive. GNSS systems become the users' best friend but offer no help in the event of a system failure,

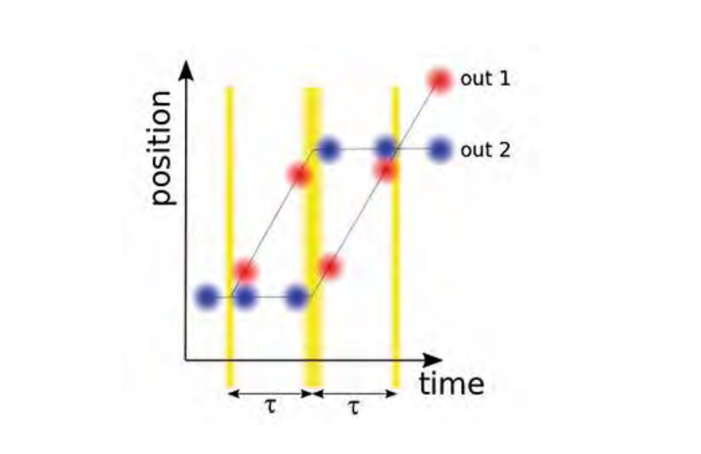

Figure 1 Schematic overview of an atom interferometer acceleration sensor. The blue/red dots represent clouds of ground state/excited atoms and the yellow lines represent laser pulses.

interference or deliberate jamming and spoofing.

A RENEWED INTEREST IN SENSING

Some users have never trusted GNSS. Commercial aircraft still carry alternative systems – including radio navigation aids - to bring resilience. How can those who have become over-dependent on GNSS get resilience back?

It is time to revisit the sensing and measuring devices from a pre-GNSS age. When John Harrison used different metals to overcome temperature effects in his famous chronometer he showed not just mechanical ingenuity but a deeper understanding of materials. Our understanding now is so much greater, not just of materials but of matter itself, and it is here where new opportunities lie.

QUANTUM CLOCKS AND QUANTUM NAVIGATORS

One example would be Quantum Technologies which harness the capability of manipulating the quantum states of individual pieces of matter to unleash opportunities not accessible with classical technology. Quantum sensors are of particular relevance to position, navigation and timing. Using laser pulses to manipulate individual atoms allows the creation of quantum superposition states, where these atoms are in two different places, or in two different energy states at the same time.

Figure 1 shows the example of an atom interferometer. Here a cloud of atoms is prepared in a vacuum chamber at micro-Kelvin temperature using the Nobel Prize winning technology of laser cooling. At this temperature the atoms become so slow, that they can be dropped like an apple. During the drop, three laser pulses manipulate the atomic quantum state. The first laser pulse is tailored to excite the atom with a 50% probability, which in quantum terms means that it places the atom in a superposition of being excited and in the ground state at the same time. The excited part of this superposition will not only have absorbed the energy of a laser photon, but also its momentum, hence start to move away from the ground state part of the superposition. The second pulse inverts the energy and momentum states of the atom and makes the two parts of the superposition converge again. At the time when they overlap, another laser pulse with 50% excitation probability creates an interference between the states. The result depends on how the trajectories differed and can be read out by counting the number of atoms in the ground versus in the number in the excited state. If, like in this example, the trajectories were split along the laser direction, then the result is highly sensitive to the acceleration along this axis. If, alternatively, one arranges the system such that the trajectories enclose an area, then the result is a highly sensitive rotation sensor. Finally, an ultraprecise clock is created, if one does not split the trajectories and just creates a superposition of energy states. Each of these instruments, accelerometer, rotation sensor and clock has been demonstrated in a laboratory environment to be orders of magnitude more sensitive than their classical counterparts. However, are these just scientific toys, or can they be used in the real world?

In 2013, the UK government has led the world in recognising the potential these Quantum Technologies have for the future and announced an unprecedented investment of £270M into the translation of these fascinating fundamental science results towards practical products. Today, the UK National Quantum Technology Program has reached £1bn and can be proud to have an internationally leading supply chain for commercial Quantum Technology products.

One of the first emerging products is a compact atomic clock, developed between NPL and Teledyne-e2v. Such a clock could provide effective holdover time during GNSS outages and also would allow to detect spoofing attempts by the associated irregularities in perceived GNSS time.

Having detected a spoofing attempt, a resilient system will need to switch over to an alternative navigation solution. Here a combination of inertial navigation and position fixes by map matching would provide a solution. Inertial navigation relies on the measurement of acceleration and rotation, in order to follow the movement of the vessel. Double integration of the acceleration in the direction given by the rotation sensor allows to extract position. However, the multiple integration of measurement makes inertial navigation units prone to rapidly accumulating errors due to bias and drift errors. Even the massive improvements in precision offered by quantum inertial sensors will not be able to overcome this issue at long time scales, as e.g. some drift might just emerge from gravity variations due to external mass distributions being misinterpreted as accelerations.

A precision gravity map is important, in order to correct for such errors. However, once such a map is created, it can also be used in a different way, creating huge benefits to a navigation system. Using a gravity sensor, such as e.g. offered by quantum technologies, one can obtain a trace of gravity over the trajectory of the vessel. Matching this trace to the best fit on the gravity map, will then provide an absolute position, which can be used to fix any drifts in inertial navigation units. With neither inertial nor gravity sensors needing any communication with the outside world, this allows a highly resilient navigation and long-term stable solution, which even works under water.

Of course gravity is not the only modality one can use for map-matching. Alternatives are magnetic maps using quantum magnetic sensors, or – in coastal waters – radar maps, where radar resolution might be enhanced by orders of magnitude using quantum oscillators.

RESILIENCE BRINGS BENEFITS

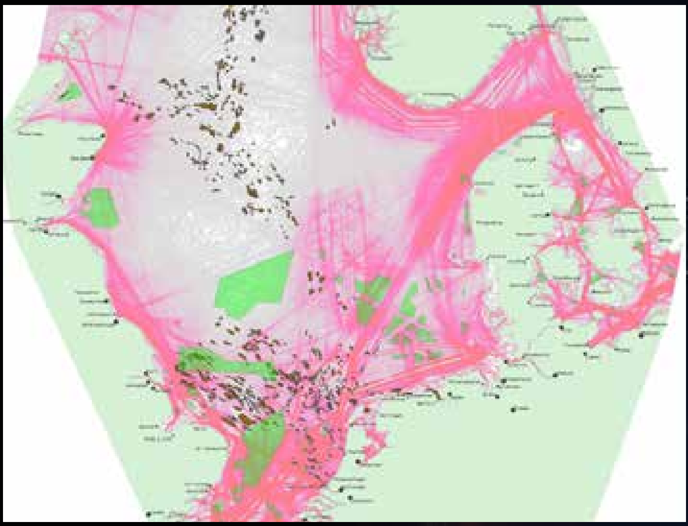

Figure 2 Complex North Sea space. Red lines are trajectories and density of shipping; green & black areas indicate locations of offshore energy installations (wind and hydrocarbon).

As a maritime nation, 95% of UK trade goes by sea. Our economy and wellbeing depend on seamless supply chains across ships, ports and inland. 'Just-in-time' logistics require dependable voyages, wending through complex sea spaces (Figure 2), congested by the increasing size and number of vessels dodging a myriad of marine users (e.g. renewable off-shore energy installations). Ships' bridges are increasingly digital, with the vessels continuously adapting their voyage plans to schedule routes with the availability of berths. Delays could lead to empty shelves in supermarkets and pharmacies.

The maritime world of e-Navigation services, with autonomous ships expected in UK ports within this decade, is acutely dependent on accurate, robust knowledge of movements of assets at sea. For mariners on the bridge (or in monitor centres ashore), reliable situational awareness and decision support require resilient, high-integrity PNT information. Such data ensures operational safety and efficiency for the timely flow of goods, with alerts for faults to avoid hazardously misleading information. Trustworthy PNT underpins speed and route changes, minimises fuel burn, reduces close encounters with other vessels (negating needs for urgent collision avoidance) and safeguards the marine environment. Developing UK PNT capability to international standards, with a compelling business case, presents technical, commercial, socio-economic and regulatory challenges. The problem has no immediate single technology solution, but Quantum Technology (QT) heralds exciting future possibilities.

A solution by 2030 across multimodal logistics requires technologies complementary to GNSS, but they must be independent, dissimilar, with no common modes of failure. The answer lies in a system-of-systems which combines disparate, precisely synchronised radionavigation technologies into a hybrid resilient navigation solution. A system of space, terrestrial and Dead Reckoning (DR) systems maximises performance and geographic coverage of PNT capability. Integrating GNSS, DR, wide-area eLoran, regional clusters of Ranging Mode (R-Mode) of the VHF Data Exchange System (VDES), coastal sensors (e.g. radar) and local systems (LOCATA at ports), optimises resilience. Additional ranging signals from space, possibly from LEO satellites, may extend coverage to oceanic voyages. However, costs mount with additional space and terrestrial infrastructure and complexity of user equipment.

Radionavigation in a quantum age should benefit from enhanced availability, greater coverage area and lower costs, with iterative technology insertion from emerging QT developments. Expensive clocks are necessary in current radionavigation systems for precise time hold-over. Future QT clocks, synchronising signal transmissions and maintaining accurate time in receivers, may reduce costs to a fraction of their predecessors, benefiting PNT performance and coverage, with possibly less infrastructure.

The advent of QT inertial measurements, a potentially disruptive technology for navigation equivalent to Harrison's chronometer in its day, could vastly reduce Dead Reckoning errors in the system-of-systems and relax dependence on frequent position fixes from radionavigation. Complementary QT gravity/geomagnetic gradient measurements, matched to high resolution maps along the inertial trajectory, could further constrain position drift. Simultaneously sensing Earth's gravity vector for subtraction from QT-sensed accelerations would determine platform motion in Earth axes in support of inertial capability.

The master mariner (safely ensconced ashore) of future autonomous vessels, weaving through marine obstacles and congestion, will demand assured situational awareness. A PNT system-of-systems enhanced by emerging QT sensors within the 2040 timescale should deliver.

CONCLUSION

For many years, resilience has been treated as a "nice to have but difficult to implement" feature. The recent progress made in the development of quantum technologies is changing the outlook. Better sensors – including clocks – bring the prospect of simpler systems with higher performing component parts, a fundamental tenet of reliability and resilience. New sensors will also bring new maps, exploiting the natural signals of gravity and magnetism without the need for costly ground and space infrastructure.

Surprisingly, into this mix of new technology there is a clear role for seemingly old-fashioned terrestrial radio navigation systems. Maybe there is no surprise as truly resilient systems have always been hybrid systems.