Quantum-Enabled Maritime Navigation
Workshop Notes

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The Quantum Enabled Maritime Navigation Workshop at the Naval Club in Mayfair represents a natural successor to previous quantum maritime technology workshops held at the University of Birmingham on March 30th, and at Trinity House on April 17th, of 2017. Both workshops recommended further work to assess the potential value of applying current innovations in quantum-enabled systems to the development of resilient PNT solutions, and to understand the requirements and needs of the maritime community.

The context for the workshop was set by the recent Blackett review into Satellite-derived Time and Position [1], which highlighted the risks arising from over-reliance on Global Navigation Satellite Systems (GNSS) for Position, Navigation, and Timing (PNT) needs. Quantum technology, a rapidly maturing field, presents pathways to realising resilient, potentially GNSS-free, PNT [2, 3, 4, 5]; however, there are scientific and engineering challenges to overcome.

This workshop was held to gain a deeper understanding of user requirements, priorities, and the tradespace for a resilient maritime PNT technology, in order to inform research and design for quantum systems. Emphasis was placed on the involvement of potential end-users early in the development cycle to inform design choices. In this manner the workshop also represents a natural step in Quantum Systems Engineering, a focus of the Loughborough research group for a number of years, and follows a series of Quantum Systems Engineering events, together with recent analysis of the potential impact, challenges, and possible shortcomings when applying classical Systems Engineering to quantum enhanced devices [6, 7].

Key messages

- There is an acknowledged and urgent need to develop more resilient PNT solutions for the maritime domain. There is an underlying similarity in needs between the military and civil domains, suggesting that there may be some commonality in technology solutions. This is important for the quantum programme, as significant demand will help to overcome

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initial barriers to realisation and to drive an economy of scale, reducing costs to a level that would be affordable for users in the maritime sector.

- There was consensus that a fundamental barrier to uptake would be developing trust in any new precision navigation system. A competitive advantage of current inertial navigation systems is aggregate performance data across operational conditions. For a new, quantum, system to have buy-in its performance must be established through in-use demonstration and testing. The necessary quantity of operational data required to validate the performance of a precision navigation system will be significant, and must demonstrate reliability and repeatability in measurements, as well as longevity. Collection of this data, even if just for quantum sub-systems, is a clear priority.

- Until quantum technologies become more mature, and better trusted, there is no particular appetite for replacing whole navigation systems with quantum counterparts. Generally any technologically novel system, including quantum, would need to offer a capability complementary to existing systems, helping to provide a 'blended' PNT solution. For this reason, integrability, compatibility, and ability to retrofit must be design focuses. Furthermore, many non-technical needs were established, including regulatory acceptance, usability, maintainability, autonomy, and impact on safety. It is important for quantum to design for all these needs, and not just for technical requirements.

- The prioritisation of needs for commercial and naval maritime operations is use case dependent. The workshop succeeded in establishing needs for general operations, and identifying criteria for a technology tradespace (see *Needs and tradespace* of the detailed notes), but the weighting of these criteria requires specific use-case analysis. Requirements for some use cases are well known (e.g. harbour approach in poor visibility, or traversing minefields in clear channels), offering a starting point for understanding how quantum could usefully contribute to a blended solution.

- In order to recommend routes to exploitation for quantum technologies, and identify use-cases for which they will be naturally valuable, detailed modelling of quantum systems is needed to predict likely device performance, and to highlight critical parameters. Due to the instability of the navigation equations, and the complexity of navigation systems, this is a challenging task and should be addressed soon, including the interfacing of quantum models to existent implementation-free navigation models.

- There is solid technical ground to expect that quantum can deliver substantial advantage to local timing capabilities, and to contribute to next-generation inertial navigation systems, but what must be established is a plan of sufficient detail and granularity to provide a robust, incremental, and structured route to exploitation that realises the overall potential of quantum, whilst providing a return on investment at each technology step.

- Beyond technical realisation, implementation of any new technology will require supporting infrastructure such as software and electronic systems, certification, hydrograhic charts (for gravity feature matching), regulatory acceptance, consultancy, and the supporting supply chain. For these to be ready for a quantum product, granular roadmapping towards the delivery of agreed technology targets is needed.

- A PNT capability is delivered by the blended system whole. The burden of delivering a performance enhancement does not directly fall upon a quantum enhancement, but is a consequence of what that enhancement enables in terms of whole-system behaviour. A comprehensive analysis of how current PNT systems function, the flexibility there may be in their operation (e.g. Kalman filter algorithms), and the limitations imposed by weakest links, is needed in order to identify the most easily realised quantum sub-systems that enables performance improvements at the whole-system level.

- Ultimately, a quantum-enabled PNT system is a product and solution, not a requirement with automatic buy-in. It is imperative that the potential benefits of quantum are substantiated in the context of realistic use, and that the path to realisation for quantum is considered as much from user and industrial perspectives, as from that of technical science.

Recommendations

- Focus group meetings to derive mission-critical parameters for specific use-cases, informing the tradepsace, and specifying concretely what advantage a quantum technology would have to offer to be valuable, are needed. These may also specify necessary modelling capability to derive technical requirements, and inform routes to exploitation. A wide variety of use cases should be covered, as quantum solutions with common applicability are likely to be most valuable overall. From the perspective of industry and end-users such focus-groups can act as risk management activities, identifying technology and performance targets, development tests, and general acceptance criteria for a new technology seeking to mitigate existing PNT risks. This conversation must be informed by the art of the possible, including some understanding of the potential architectures and performance of blended quantum-enabled solutions.

- There are various UK activities looking at improving the resilience and performance of maritime navigation systems. It would be helpful to establish a comprehensive view of these, highlighting how quantum could interface with them, enabling information sharing, and ultimately developing a unified body of knowledge for both academia and industry.

- Engineering-quality models of quantum sub-systems and devices need to be developed; the sooner these are available, and used to inform design, the more likely it is that first-generation quantum technologies will be valuable.

- Technical roadmapping, guided by a systems engineering perspective and system modelling results, needs to be undertaken to establish common goals, and to communicate clearly to a wider community what it is that quantum technologies can offer.

Detailed Notes

The need for GNSS-free PNT

- There has been an emerging understanding that over-reliance on GNSS for position and timing has resulted in it becoming an effective single point of failure across many sectors of the UK economy. A five-day disruption of GNSS has been estimated to potentially cost the UK economy £5.2Bn, with the maritime sector representing 21% of the national reliance on GNSS [1]. Consequences of GNSS loss are significant for both commercial and naval maritime use cases. In the former, GNSS loss could prevent harbour approach and docking, degrade quality of logistics costing fuel and time, and introduce risk in congested or complex sea spaces. The severity of GNSS loss is likely to increase as sea spaces become more complex, more congested, and as autonomous ships are realised. In the latter, GNSS loss can affect safety and capability, and a technology that could help guarantee resilient PNT in all circumstances could present material advantage for surface and sub-surface operations. There was an acknowledged sense of urgency to addressing this issue, and with it a technology pull potentially willing to invest in new solutions.

- The consequences of GNSS loss are multi-faceted, loss of timing information can cause desynchronization with communications networks, loss of positional information has consequences to navigation (especially in congested or dangerous waters), and the General Lighthouse Authority reported that their testing had revealed emergent failures in bridge systems due to systemic reliance on timing information within sub-systems. It is possible to use existing oscillator technologies (quartz, caesium, rubidium, etc.) to provide some timing holdover, however, whether for reasons of cost, SWaP, or awareness, these are not generally or consistently employed in the commercial maritime sector.
- The demand for resilient PNT is growing due to technological advances and the increasing complexity of water spaces. Regulations (e.g. emissions borders), congestion, and man-made ocean features such as wind farms are causing the complexity of maritime navigation to rapidly increase, increasing demand for resilient PNT. Similarly, future technologies such as autonomous shipping may increase this demand. Regulation for autonomy may specify a need for position certification, this trust requirement may mandate good inertial backup systems or alternative means of position fixing.
- There are also developing use cases for unmanned underwater vehicles, for tasks such as sea bed/feature monitoring (e.g. checking fibre lines), and for surveying in deep sea mining. These will require GNSS-free PNT, may involve multiple Unmanned Underwater Vehicles (UUVs) that must remain in communication and know their relative positions, and could require highly efficient navigation due to limited ranges.
- For commercial shipping, loss of GNSS can result directly in loss of profits; if communications are lost ships may have orders to halt until communications can be re-established. This, as well as decreased navigation performance, can hurt the already tight bottom line for shipping companies.
- In the past, uptake in new technology by the commercial maritime sector have primarily been triggered by the introduction of regulation, which can be slow due to the need to reach international accord.

Needs and tradespace

- The technical needs and tradespace for commercial and naval surface ship PNT were found to be very similar. Ideal capabilities and performance for a transmission free accurate navigation system were specified: Capable of going long periods (mission duration) without calibration or external reference in every-day conditions; Avoiding any radio-frequency emissions; Working globally; Having an accuracy of 10m in absolute position, down to 1m on demand for specific uses; Sufficient integrity, availability, and continuity, to navigate a 100m swept channel minefield; And enabling or including systems that allow multi-vessel collision avoidance for congested regions. These were specified for a Naval vessel, but closely matched those for large commercial vessels on the final stages of harbour approach in poor weather; in the commercial case requirements on mission duration and radio communication are relaxed, but the other underlying needs matched well.
- Outside the technical domain needs differ. Commercial shipping is highly constrained by both through-life and upfront costs, there is a willingness to spend between £5000 and £50000 on a navigation system depending on the value of the vessel and its contents, and

it is neither common, nor required, for commercial vessels to have inertial backups. It was noted that regulation drives a lot of change in the commercial world and is slow to introduce. This is in stark contrast to military navigation grade systems that can cost £1m+, and where maintaining a lead in capability is a priority.

- Integrity and resilience were identified as critical needs for both commercial and naval maritime sectors. One must be able to assess the current trustworthiness of position information, and any means quantum can contribute to that would be valuable. Quantum was viewed as an additional information source, which could contribute to an overall 'blended solution' without removing existing information sources. Additionally, upgradability of systems, and ability to retrofit, was viewed as important by both communities, in particular to prevent the cost associated with replacing whole systems (and also integration challenges associated with retrofitting whole system replacements). For these reasons, candidate quantum solutions will have to be designed with compatibility and integrability in mind. This also implies a means to gradually transition from testing quantum, having quantum enabled systems, and eventually to having systems with a fundamental reliance on quantum technologies through the introduction of suitable integrable sub-systems.

- Space on vessels is limited, and introducing large additional systems is not possible. For this reason, the idea of quantum being introduced in stages of small-subsystems, first separate from the navigation system to improve integrity and build trust, and then integrated, had support.

- The impact of any new technology on crew must also be considered. There was consensus that any increase to the complexity of a navigator's job would not be acceptable, especially in the commercial world where crew sizes and training levels are decreasing, and autonomy is increasing. Usability of a quantum system, including its display on electronic chart systems, is of great importance and must not generate new avenues for human error. This also affects repair and maintenance, the process for a quantum system including at sea initialisation would need to be similar to those for current systems, and not require specialist expertise.

- A fundamental need for both commercial and naval systems is trust. A source of competitive advantage for existing systems and established suppliers is the vast quantity of aggregate data on their performance across operational conditions. If quantum is to be considered for technology selection, there is an urgent need to start understanding and substantiating performance through in-use demonstration and testing. The quantity of operational data required to assess performance should not be underestimated, and it was the general view that demonstration and testing of even simple quantum sub-systems should be a priority. This also requires the development of validation criteria, specifying what data sets would demonstrate acceptable performance.

- Tradespace analysis for commercial and naval maritime PNT revealed the following axes: Usability and human interface; Upfront and through-life cost; Accuracy; Assurance, integrity, and resilience; Impact on safety; Upgradability and future-proofing; Integrability and capability to retrofit; Regulatory acceptance; and Size, Weight, and Power. It was noted that the prioritisation of these needs would depend on the specific use case, and the rest of the blended solution, and hence should be considered in detail on a per use case basis. It was also noted that the commercial maritime community viewed GNSS-loss as a cyber-security problem, and advised it was framed as such to best encourage uptake and generate understanding.

- For dived vessels, anything that reduces the 'pool of errors' would be valuable. For quantum, this could be through better navigation solutions with slower error accumulation, or through position fixing via gravity feature detection. Here quantum may be especially valuable as it makes available a means of covert position fixing. An application of quantum may also be the detection of unexpected gravitational features, for example other vessels.
- To realise a quantum technology solution a variety of readiness levels need to be considered, not just Technology Readiness Levels, but Manufacturing Readiness Levels, System Readiness Levels, Integration Readiness Levels, and Autonomy Levels. Delivery is more than developing mature sub-systems, and requires the whole lifecycle, integration, and supply chain to be considered.

Technical challenges

- High performance inertial navigation systems are complicated and complex, the latter due both to the integration problem and the underlying instability of the navigation equations. It is a significant challenge to engineer good inertial navigation systems, as well as to model their behaviour.
- Significant improvements to one navigation parameter do not result in a similar improvement to the navigation solution, it is a system of weakest links; modelling is required to determine where improvements to sensor capability will result in substantial improvements to navigation. An initial expectation is that restriction of vertical drift (e.g. through quantum gyroscopes) could improve existing navigation systems, and be achievable through a bolt-on quantum system.
- The unstable nature of the navigation equations means that high-order modelling terms can be very significant to describing device performance. This mandates detailed modelling of the quantum system and its behaviour, and suggests that the approximation-led modelling often undertaken in physics would not be sufficient to predict the behaviour, or aid in the design, of a quantum navigation system.
- Sensitivity of inertial navigation systems to their environment is significant (e.g. temperature fluctuations). Consequently, the effects of environmental changes on a quantum navigation system need to be investigated in detail, and even small variations may significantly affect performance. Design for reliability must be considered with this in mind.
- Measurement frequency (integration step-size) is critical for navigation systems; even an inertial navigation system with perfect sensors will rapidly lose accuracy if its repetition rate is low. Current quantum systems are far from the necessary repetition rates, and display a trade-off between measurement accuracy and measurement time, suggesting that, until such issues are resolved, early realisations of quantum PNT systems will be quantum assisted rather than fully quantum.
- Integrity is not associated with a unit of merit, it is approached qualitatively with systems having 'high' or 'low' integrity. There is an open question as to how we define integrity, and how we validate integrity. This is fundamentally a Systems Engineering problem, and not unique to quantum systems. Solving this problem will affect all areas of systems acceptance, and perhaps help in defining future regulation associated with records of position (especially in the context of autonomy). As the quantum community has a need to demonstrate the advantage of a quantum solution, they may benefit from considering how best to to technically describe, and validate, system integrity during their own design

process. This may also be a point on which the maritime and quantum communities can engage with systems engineering bodies (e.g. INCOSE).

- The IMO resolutions A.1046 and A.915 define GNSS-based accuracy, integrity, availability, and continuity requirements, and the IMO performance standard MSC.401(95) sets out operational and functional requirements for current GNSS systems. The quantum community are likely to find these useful in informing design of future technology, not least as they describe current test and acceptance criteria.

Applicability of quantum

- In a conventional inertial navigation system small uncertainties or fluctuations in the local gravity field, and in the precise shape of the earth, are an important source of error. Quantum sensors to measure local gravity could both assist the production of more accurate gravity maps and provide an additional modality for reducing the overall 'pool of errors'.

- As quantum evolves it will be important to understand how best to architect navigation systems that utilise it; current navigation systems are the result of decades of engineering taking advantage of the available technology, one should not assume that an optimal use of quantum will be architecturally analogous.

- In the medium and long term quantum-enabled sensors (e.g. gyros) have sound physical underpinnings to deliver significant improvements in performance, these developments need to be incorporated iteratively as they emerge. The widespread value of quantum may lie in improving the whole PNT solution, rather than satisfying a singular 'killer' need.

- Quantum-enabled calibration of inertial sensors could be the closest valuable technology iteration, improving performance of existing and future conventional systems at limited cost, starting to build trust in the technology, and deferring the engineering challenges associated with compliance, integration, and lifecycle, for a deployed navigation system.

- The physics community is eager to engage, but, in order to assess how quantum can best contribute to a blended solution, need interfaces to knowledge about the current state-of-the-art in blended navigation systems, including details on design and performance. Furthermore, as the development of a quantum navigation system must be needs driven, with a focus on integrability, it is important that a formal Systems Engineering process is applied to any quantum navigator projects, especially with a view to bridging user and developer communities, and sharing knowledge.

Next steps

- Understanding the benefit that users and ship operators might realise from adopting quantum technologies will require the development of well-defined use cases. Investment decisions will be based upon achieving levels of system operation which would enable users and ship operators to realise benefits that provide an acceptable return on investment for all parties, thus it is in the interest of the quantum community to link the technical improvements quantum may offer to usage outcomes and bottom lines. Use cases will also inform the engineering and design of quantum solutions; if current demonstrators can be designed with end-use in mind, translation to higher readiness levels may be easier and require less re-engineering.

- The workshop discussions made clear that there are problems, each contributing to operational risk, looking for solutions. Thus, a sensible first step may be to run solution-agnostic focus groups specifying, in detail, key risk factors and associated use cases. Through this work the identification of domain specific needs, analysis of critical performance parameters, detailed tradespace translation, and defining of acceptance and validation criteria, can be undertaken. One can view this as a type of risk management activity, completing which enables the recognition of problems for which quantum may be a reasonable mitigation, and opens a path to a full benefits appraisal for a quantum solution.

- Whilst the prior point may open the possibility of assessing the benefits of a quantum solution, in order to make the benefits case detailed modelling of quantum systems is needed, and the interfacing of these models to existing implementation-free navigation system models. This will be necessary in order to determine the critical performance parameters for quantum systems, as well as to better understand how they might optimally contribute to a blended PNT solution. Until some predictions can be made in this domain, it is impossible to assess how, where, and if, quantum can significantly mitigate existing problems.

- There is a demand for clear technical roadmapping. The maritime community would like to know how quantum can deliver PNT solutions, and how this can be supported. Similarly, an enabling structure greater than the technical realisation of quantum technologies is needed, including integration of technology into electronic systems, data display, certification, gravity mapping, consultancy, and the development of a supply chain. For these to be ready for a quantum product, granular roadmapping towards the delivery of agreed technology targets is a priority need.

- The UK defence maritime sector is a comparatively small market which procures limited numbers of systems with comparatively long periods between orders. Establishing a viable supply chain for quantum components will require civil and military quantum systems to be based upon common enabling technologies. Therefore, it will be important to identify applications in the civil maritime sector that can provide sufficient demand to enable supply of quantum systems. This quantity of demand will also drive improvements to the manufacturing process, improving system quality and decreasing system cost.

- There are numerous concurrent activities being undertaken regarding resilient PNT, and quantum technology development; it is important to identify all relevant activities, and enable knowledge sharing between them. Part of the UK's competitive advantage lies in its ability to organise activities in a unified cross-disciplinary way.

- Quantum is not the only competitive solution in this space, E-Loran, for example, may be able to mitigate some of the PNT risks identified. It remains the case that through needs and tradespace analysis, technical modelling, and systems engineering, we must identify where quantum can have the greatest impact to the blended PNT solution.

- The challenges of implementing a quantum PNT solution are unlikely to be overcome in one step, this may be overcome through an iterative strategy to technology development. Each iteration must be specified such as to provide a return on investment, with the overall development route to realising quantum's potential advantage. Iterative development and delivery strategies have been applied to great success in the semiconductor industry, and, guided by appropriate systems engineering, may be of value to quantum technologies.

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