Quantum Sensors in the Maritime Environment

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ABSTRACT

A major scientific thrust from recent years has been to try to harness quantum phenomena to increase the performance of a wide variety of information processing devices. Quantum Information Science (QIS) has emerged as a scientific undertaking that promises to revolutionize our information infrastructure. In particular, QIS offers the possibility of quantum sensors. That is, sensing devices that exploit quantum phenomena in such a way that they perform significantly better than their classical counterparts. In this tutorial we will briefly describe recent theoretical research that suggests that by harnessing quantum phenomena we can improve traditional sensing devices such as radar/lidar, magnetometers, and gravimeters. Indeed, quantum radar appears to be possible because of recent promising theoretical and experimental results regarding manipulation, entanglement, propagation, detection, and interferometry of quantum states. At the same time, many theoretical and experimental questions remain open (e.g., fast and efficient entanglement generation, single photon detectors, quantum signal processing, and quantum memories). Furthermore, it is important to notice that quantum sensors are not intended to replace traditional sensing systems, but to work together in order to leverage the benefits of both. Clearly, quantum sensing appears to be a "high-risk / high-payoff" endeavor that deserves further scientific and engineering consideration, research, and discussion.

When two quantum particles are entangled, there exists a high degree of correlation that cannot be matched even by perfect classical correlations. In a quantum radar/lidar system, an entangled pair of photons is produced; one photon is kept within the sensor while the other is emitted towards a region of space. Then, entanglement correlations are used to distinguish between noise photons and those signal photons that are bounced back to the detector due to the presence of a target. As we will argue, this system can operate in low brightness levels (using a small number of signal photons) and in an extremely noisy environment, making the sensing radiation practically invisible to those who don't have access to the entanglement correlations. A perfect application of quantum lidar in the blue-green optical regime is as an aid for navigation of underwater vehicles traveling under the Arctic ice canopy. As it is well known, the precise navigation of underwater vehicles is a difficult task due to the challenges imposed by the variable oceanic environment. It is particularly difficult if the underwater vehicle is trying to navigate under the Arctic ice shelf. Indeed, in this scenario, traditional navigation devices such as GPS, compasses and gyrocompasses are unavailable or unreliable. In addition, the shape and thickness of the ice shelf is variable throughout the year. Current Arctic underwater navigation systems include sonar arrays to detect the proximity to the ice. However, these systems are undesirable in a wartime environment, as the sound gives away the position of the underwater vehicle. In this tutorial we briefly describe the theoretical design of a quantum imaging system that could allow the safe and stealthy navigation of underwater Arctic vehicles.

Another example of a quantum sensor is a magnetometer that exploits the magnetic bias in entangled singlet states in a radical pair as a part of a biochemical reaction mechanism (RPM). It

is conjectured that such magnetic bias serves as an inclination magnetic compass in migratory birds. This is an example of the new field of quantum effects in biological systems. Interestingly, such nanomagnets could be synthesized in the laboratory, allowing the construction of low-cost, small-size, low-power, medium sensitivity magnetometers (in the micro-Tesla regime). While there are more powerful magnetometers available (e.g. based on squids and the Hall effect), these biologically inspired quantum sensors are easy to mass-produce and mass-deploy. These quantum magnetometers could be highly relevant for taking a new approach to magnetic anomaly detection (MAD) for anti-submarine warfare (ASW). Indeed, while the current approach is to employ a single, but very sensitive magnetometer, our proposed approach is to employ sensor data fusion on a very large number of low-cost, low-power, small-size, medium - sensitivity quantum magnetometers. In this tutorial we will briefly discuss the potential advantages of the new approach, as these sensors can be mass-deployed in the ocean environment or used to quickly convert existing airborne and maritime assets into sensor platforms.

Finally we will discuss quantum gravimetry. Once again, by exploiting the quantum entanglement of entangled states made of many particles, it is possible to design very high sensitive gravimeters. For instance, the best-known approach currently employed in gravimetric sensing is the use of heavy atom interferometry. However, the sensitivity of this technique is bounded by the mass of the atoms used in the experiment to about 10^{-9} (heavier atoms produce higher sensitivity, but adequate heavy atoms to perform atomic spectroscopy are difficult to come by). On the other hand, our approach to quantum gravimetry appears to only be bounded by the effects of a yet unknown quantum theory of gravity. As we will discuss in this tutorial, these quantum gravimeters could be used in a variety of ways in the maritime environment. For instance, these quantum sensors could be used to create very highly detailed gravimetry maps and navigation tools for non-GPS navigation. Alternatively, these quantum sensors could be used to detect heavy ore deposits in the bottom of the sea or to detect the presence of heavy underwater vehicles.

In order to take full advantage of the many opportunities offered by our oceans, we need to develop improved sensors. We believe quantum sensors are the best alternative currently offered by modern science. Therefore, the development of quantum sensors is crucial to ensure the correct, lawful, secure, and efficient use of our oceans.

LEARNING OBJECTIVES

This course will enable the student to:
- explain the difference between classical and quantum information
- explain the difference between classical and quantum sensing
- describe the role played by quantum entanglement and superposition in the design of quantum sensors
- describe how the detrimental effects of environmental quantum noise can be mitigated
- explain the basic design principles to design and develop novel quantum sensors
- summarize recent research results that showcase the feasibility of quantum sensing
- describe the potential applications and advantages of quantum radar, lidar, photo-detection, magnetometry, and gravimetry
- compare the theoretical performance of quantum and classical sensing devices.

PRESENTATION OUTLINE

- ➢ Introduction and welcome (15 mins)
- ➢ A quick glance at quantum phenomena (45 mins)
- ➢ Standoff quantum sensing (radar + lidar) (60 mins)
- ➢ Break (15 mins)
- ➢ Quantum magnetometry (45 mins)
- ➢ Quantum gravimetry (45 mins)
- ➢ Final discussion (15 mins)

BASIC BIBLIOGRAPHY

1. M. Lanzagorta, J. Uhlmann and S. E. Venegas-Andraca, "Quantum sensing in the maritime environment," *OCEANS 2015 - MTS/IEEE Washington*, Washington, DC, 2015, pp. 1-9.
2. J. Uhlmann, M. Lanzagorta and S. E. Venegas-Andraca, "Quantum communications in the maritime environment," *OCEANS 2015 - MTS/IEEE Washington*, Washington, DC, 2015, pp. 1-10.
3. S. E. Venegas-Andraca, M. Lanzagorta and J. Uhlmann, "Maritime applications of quantum computation," *OCEANS 2015 - MTS/IEEE Washington*, Washington, DC, 2015, pp. 1-8.
4. M. Lanzagorta, *Quantum Radar*, Morgan & Claypool, 2011.
5. M. Lanzagorta, *Underwater Communications*, Morgan & Claypool, 2012.
6. M. Lanzagorta, *Quantum Information in Gravitational Fields*, IOP, 2014.

TARGET AUDIENCE

Scientists, engineers, technicians, or managers who wish to learn more about quantum sensors and their potential applications to radar, lidar, photo-detection, magnetometry and gravimetry. Undergraduate training in engineering or science is assumed.

COURSE LEVEL

Introductory

COURSE LENGTH

Half-day (4 hours);

FORMAT:

Oral presentation supported by PowerPoint slides. No further requirements beyond a projector and a screen.

BIOGRAPHICAL SKETCH OF INSTRUCTOR

Dr. Marco Lanzagorta is a Research Physicist at the US Naval Research Laboratory in Washington DC. Dr. Lanzagorta is a recognized authority on the research and development of advanced information technologies and their application to combat and scientific systems. Dr. Lanzagorta has over 100 publications in the areas of physics and computer science, and he authored the books *Quantum Radar* (2011), *Underwater Communications* (2012), and *Quantum Information in Gravitational Fields* (2014). Dr. Lanzagorta received a doctorate degree in theoretical physics from Oxford University in the United Kingdom. Before joining NRL, Dr. Lanzagorta was Technical Fellow and Director of the Quantum Technologies Group of ITT Exelis, and worked at the European Organization for Nuclear Research (CERN) in Switzerland, and at the International Centre for Theoretical Physics (ICTP) in Italy.

INSTRUCTOR'S SELECTED PREVIOUS PRESENTATIONS ON THE TOPIC (available upon request):
"Quantum Sensors" half-day course at the 2016 SPIE Defense and Security Symposium.
"Quantum Radar" plenary talk at the IEEE Radar Conference 2017.
"Quantum Computation" half-day course at the 2017 SPIE Defense and Security Symposium.
"Quantum Sensing in the Maritime Environment", paper presented at the 2016 IEEE/MTS Oceans Conference, Washington DC.
"Quantum Communications in the Maritime Environment", paper presented at the 2016 IEEE/MTS Oceans Conference, Washington DC.
"Maritime Applications of Quantum Computation", paper presented at the 2016 IEEE/MTS Oceans Conference, Washington DC.

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