UDT 2019 – The Suitability of Quantum Magnetometers for Defence Applications

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Abstract — Quantum technologies are beginning to move out of laboratory environments and into industrial applications. Recent funding announcements such as the EU Quantum Flagship and UK National Quantum Technologies Programme will only accelerate their adoption further. One technology that appears to be more mature than most is the development of quantum magnetometers, indeed some devices are now commercially available. These quantum devices will offer increases in sensitivity over traditional devices by several orders of magnitude. As an example a typical fluxgate magnetometer can resolve changes in magnetic fields below 1nT with a noise floor of less than 6pTrms/sqrtHz, a quantum magnetometer aims for a resolution of a few pT or less with a noise floor of fT/sqrtHz. A quantum magnetometer ideally will have a performance rivalling or exceeding that of a Superconducting Quantum Interference Device (SQUID) magnetometer but without the need for cryogenic cooling and in a much smaller form factor. This increased sensitivity and reduction in noise floor will have benefits across a number of industries. This document will specifically focus on use cases for defence applications.

Thales UK has investigated the use of two promising magnetometers developed in conjunction with two leading UK universities and considered their applicability to defence applications. These investigations have including more traditional detection of ferrous objects at distance, such as in MAD sensors, but also detection of non-ferrous objects at shorter ranges. The latter resulting in the largest detection range for magnetic induction tomography reported anywhere in the world.

This paper presents the outcomes of these tests and considers other use cases for defence, such as for non-destructive testing and navigation, which may be enhanced with these technologies.

1 Introduction

Magnetometers are used in many different fields both in the defence and civil sector. A quantum magnetometer offers a significant increase in sensitivity over traditional devices and it is this step change in performance which that necessitates a reassessment of their use cases.

Figure 1 [1] gives an overview of applications that require magnetic sensors alongside the types of sensors employed. It is not the intention of this document to describe all use cases or discuss all sensor types but the applications are varied in their nature and sensing requirements.

The figure plots the application against the required minimum detectable field (sensitivity) and the dynamic range required. In the majority of cases these are the key user requirements. Although the form factor is important, the application can often be tailored to suit device performance or alternative magnetometer types selected.
Figure 1, modified from a diagram produced by Díaz-Michelena [1], also contains a bar representing the potential performance of a quantum magnetometer. A dashed section indicates the extremes of performance that would be desirable for these devices.

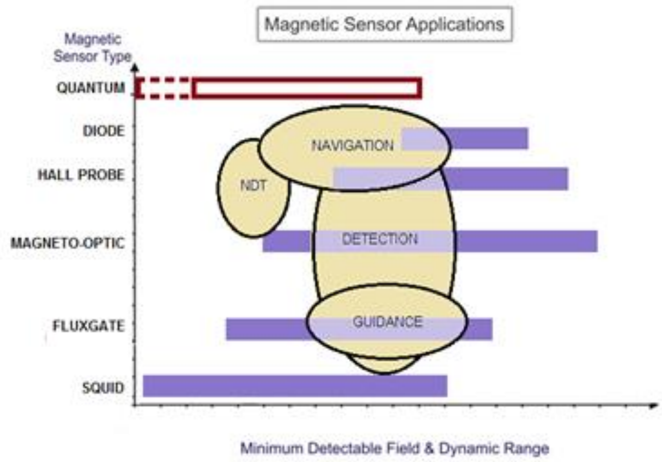

Fig. 1. Magnetic Sensor Applications

2 Uses

Magnetometers are used in many varied applications in the defence and security domain, although these can be categorized into a four main areas;

- Remote detection
- Remote inspection
- Vessel protection
- Navigation

Remote Detection

Magnetometers are used for remote detection of underwater objects but other technologies, such as sonar for the underwater domain, can offer longer detection ranges. If the use of magnetometers is to be accepted they must offer equivalent detection ranges, lower false alarm rates or detection of low signature targets in difficult environments such as the surf zone. It is possible that magnetometers could be used in conjunction with other sensors to aid in detection, identification and classification of targets.

Remote detection of targets requires a highly sensitive device with low self-noise in order to maximise the detection range. The bandwidth of the sensor should be designed to match the typical signatures of the targets. This ranges from DC to several kHz to allow detection of motors and other stray field sources on platforms. A typical magnetometer used in defence applications is the Bartington Instruments Ltd Mag03, a versatile device with a frequency response from DC to 3kHz. The noise floor is from 6-20pTrms/√Hz at 1Hz dependant on the version [2].

The form factor of the device and power requirement will ultimately determine the platform from which the magnetometers could be deployed. A larger but highly sensitive and low noise device could be installed in a tow fish, a body designed to be towed behind a vessel. This has the benefit of removing the sensor from the magnetic field produced by the platform, a source of background noise. This technique is used in the Oil and Gas industry for detection of unexploded ordinance (UXO) during sea bed surveys.

An alternative deployment method would be to install the magnetometer within a drone; this may be an unmanned aerial vehicle (UAV), Unmanned Surface vessel (USV), Remotely Operated Vehicle (ROV) or unmanned underwater vessel (UUV). The requirements for sensitivity and bandwidth would be the same for all these platforms but for UAVs this would require the device to be lightweight, have a small physical volume and very low power. USVs ted to be larger and although power, weight and space are limited the constraints on the device design are not so stringent. UUVs sit somewhere in the middle of these two unmanned platforms. For UUVs a major limiting factor is the battery life, determined by the power demands of the propulsion and on board systems.

An ROV is distinct from a UUV in that it is tethered to a platform via an umbilical; this would alleviate the constraints on power supply or system size by using the cable to supply power or fibre optic connections.

Another deployment method would be to install the device on a large vessel such as a ship or submarine, either mounting on the hull or installed within other deployed sensors such as towed bodies. The power demands of the sensor become less critical in this instance. The sensor head could be positioned remotely from the inboard equipment and connected via a fibre optic link. This would allow for a smaller form factor for the sensing head.

A further option would be to install the magnetometers within a deployable unit, for a sonobuoy type device the key requirements would be similar to those of a sensor fitted to a UAV.

Magnetic Anomaly Detection (MAD) is a technique used to detect the magnetic signature of submarines, typically from aircraft such as the Lockheed Orion P-3C patrol aircraft (Figure 2) or SH-60B Seahawk helicopter [3]. The high sensitivity of a quantum magnetometer may increase either the depth of detection of objects or allow the aircraft to fly at a higher altitude and survey a larger search area.

Figure 2 – MAD Rear Boom Mounted on Orion P3-C Aircraft

Mines, Improvised Explosive Devices (IEDs) and UXO detection either at sea or on land remains a well-established operational problem. Searching for objects in shallow waters and the surf-zone offer particular challenges to traditional detection methods where various sensor types have been trialled without a satisfactory solution.

Vector magnetometers have been proposed for buried object detection and trialled in shallow water integrated into a UUV with some success [4]. The use of quantum magnetometers could, when combined with other sensors, present a viable option for detection of these objects, even in cluttered and acoustically noisy environments.

Two further possible remote detection use cases could be detection of tunnels or, after an environmental disaster, detection of buried persons. These applications would require extremely sensitive devices that can scan the surrounding environments for voids.

Remote Inspection

Thales UK and UCL have recently conducted a research task to develop magnetometers under Innovate UK project 131885 [5]. The main technique researched was magnetic induction tomography (MIT), tomography being an imaging technique that produces slices, or sectional, images of the object under inspection.

It has been demonstrated that metallic objects can be imaged using MIT even through screening materials [6]. This has applications in fast screening of parcels or for screening containers at borders. The ability to determine the contents of buildings is an important operational problem in both the defence and security domains, which MIT may be able to address. MIT may be able to complement existing solutions such as high-bandwidth radars which offer limited range and resolution and are therefore probably only a partial solution.

The potential for screening containers at borders is a technical challenge that is particularly relevant at the present time.

For fast screening of parcels or containers the key requirements for a device would be sensitivity and noise floor. The form factor and power requirements can be offset if the technology provides a viable solution.

Other objects that could be considered for screening are vehicles, luggage and passengers.

For the maritime domain mine hunting is a key naval capability. UUVs and remotely operated vehicles can be used to inspect suspicious objects detected by the vessels sonar. These devices are sent ahead of the main platform and use video cameras or high frequency sonar to image the object before deploying explosives, cutting chains or allowing the operator to dismiss the object as a false alarm. A magnetometer could be used to image objects in cluttered, noisy environments where video or acoustics are not suitable.

Vessel Protection

To reduce the risk of detonating magnetic influence mines vessels are fitted with degaussing systems. A degaussing system consists of a series of cables located around the ship through which a DC current is applied. These coils produce a magnetic field which can be used to compensate the magnetic signature produced by the vessel. The control for these coils can be either open loop or closed loop. An open loop system takes in in-feed from a magnetometer or magnetic map for the local magnetic field, this then determines the current to apply to the coils to compensate the induced magnetic signature. A closed loop system actively measures the local magnetic field using multiple magnetometers located around the vessel and this creates a feedback loop that reduces the signature of the vessel to the minimum practicable with the coil layout. Fluxgate magnetometers are used for this purpose but small, low power, sensitive devices could support further signature reductions in a closed loop system.

To monitor the magnetic signature of vessels and establish initial settings for the degaussing system the magnetic signature of a vessel is measured using an undersea range. The undersea range consists of an array of magnetometers carefully positioned on the sea bed. An issue occurs in multi-influence ranges in that the sensor positioning requirements for other signature types, such as acoustics, is much different from the magnetometers. The spacing of an array of hydrophones used to measure the acoustic signature is too great to currently allow measurement of the magnetic signature with a reasonable signal to noise level. The quantum magnetometers could overcome this through an increased sensitivity at ranges required for acoustic measurements.

Navigation

One of the key benefits of quantum magnetometers, aside for the increased sensitivity, is the removal of the need to calibrate the device. This could have applications in navigation, particularly in GPS denied environments. Quantum magnetometers tend to be scalar devices rather than vector magnetometers which are traditionally used in navigation. Some organisations have been researching atomic magnetometers (NAV-CAM) [7] and Nitrogen vacancy (NV) devices [8] for use in navigation with reported success.

The NAV-CAM device combines a closed-loop, fixed-field alkali Electron Paramagnetic Resonance (EPR) magnetometer coupled with a dual-isotope Nuclear Magnetic Resonance (NMR) magnetometer using a single vapour cell to produce a device that can be used for navigation of vessels.

The NV device works by detecting ripples in the Earths' field and detecting previously mapped anomalies. Once a reference point is determined from these anomalies the device can be used for navigation without the need for external communications such as from satellites.

An quantum magnetometer using vapour cells can also be used to detect the inertial precession of nuclear spins with high sensitivity, in addition to measuring the ambient magnetic field as its' primary mode of operation. For gyropscopes the stability requirement of is very stringent, a stray magnetic field of 1 fT would cause a false spin precession rate for ^{3}He of about 0.04 degrees/hour which is greater than would be acceptable in a navigation-grade device. Presently spin-exchange-relaxation-free (SERF) magnetometers can achieve this level of magnetic sensitivity, allowing it to be used for cancelation of stray magnetic fields and enabling a competitive nuclear-spin rotation sensor [9]. Other devices such as NV or vapour cell devices are maturing rapidly and could also offer solutions in this application in a combined sensor package.

3 Quantum Magnetometer Performance

Thales UK has investigated two promising technologies developed by leading UK universities to assess their potential for maritime applications. The AMMIT magnetometer (Atomic Magnetometer for Magnetic Induction Tomography) developed by University College London (UCL) and a device developed by the University of Strathclyde through the Innovate UK funded MagCell project.

A quantum, or atomic, magnetometer typically consists of a laser, a gas cell filled with Caesium, Rubidium, Helium or Potassium vapour and a photodetector. These materials possess a property known as spin, a form of angular momentum for elementary particles. Since the have spin they also have a net magnetic moment which can only assume discrete orientations governed by an external influence, such as an applied magnetic field, and the spin number. The method of operation is well described by Marmugi [6] and shown in Figure 3. In Figure 3A the initial state of the vapour is shown, optical pumping with a laser occurs in 3B which aligns the spin of the atoms in the vapour and they process at a known frequency. In Figure 3C the total magnetic field, such as that from a target, causes a shift in the rate of procession which is known as the Larmor frequency. This frequency is proportional to the magnitude of the external magnetic field. As it is a fundamental property of the material any device that exploits this effect does not require calibration. Figure 3D suggests that at this point magnetic field measurements can commence.

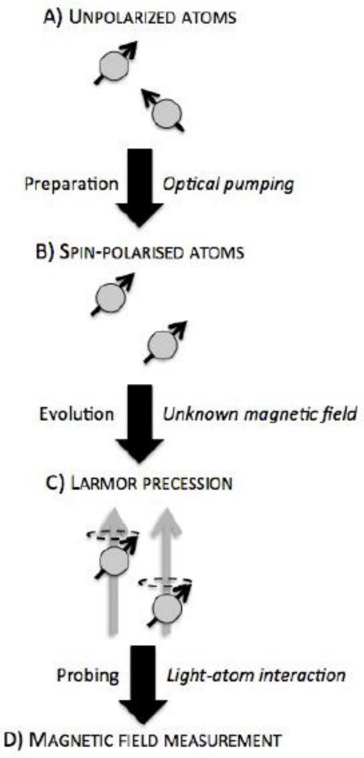

Figure 3 – Simplified Method of Operation [6]

3.1 AMMIT

The AMMIT device could be considered an active system, to use sonar parlance. An AC field is generated by a coil which then induces eddy currents within a conductive target. The eddy currents created in the target produce a secondary magnetic field which is at the same frequency to the exciting field. A phase sensitive detection scheme referenced to the primary field extracts the amplitude of the secondary field and its phase lag. The presence of a target is detected by measuring perturbations to the total magnetic field [10]. The concept is shown in Figure 4.

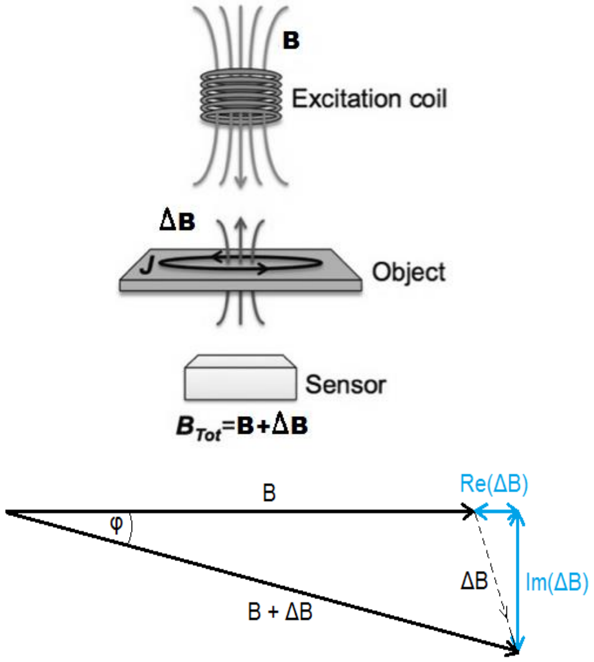

Figure 4 – Secondary Magnetic Field Measurement from Eddy Current Generation

Disruptions in the eddy current generation can indicate cracks in conductive mediums, this has been demonstrated by Deans [11] using a conductive (Aluminium) target. This could be used in weld inspections and non-destructive testing of parts.

Although active transmissions are often avoided in the underwater domain, the exception being in minehunting, this magnetometry approach triggers an unavoidable response in a conductive target.

The magnetic field produced by the eddy currents induced in the target causes a change in the polarization rotation of the Rubidium vapour which creates a measureable change to the amplitude and phase of the laser light detected by the photodetector.

Thales UK considered that this may be a technique and sensor that could be used to detect buried objects or targets in cluttered environments such as the surf-zone. A series of experiments were conducted at the Thales UK Underwater Test Facility – Waterlip Quarry, shown in Figure 5.

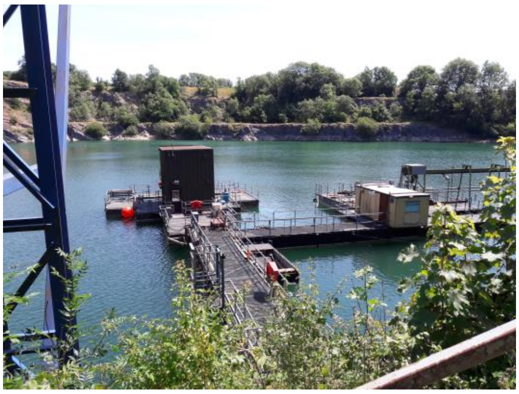

Figure 5 – Thales UK Underwater Test Facility – Waterlip Quarry

The experiments consisted of moving a non-ferrous, conductive underwater target beneath the AMMIT sensor and recording the change in response. The experimental setup is depicted in Figure 6.

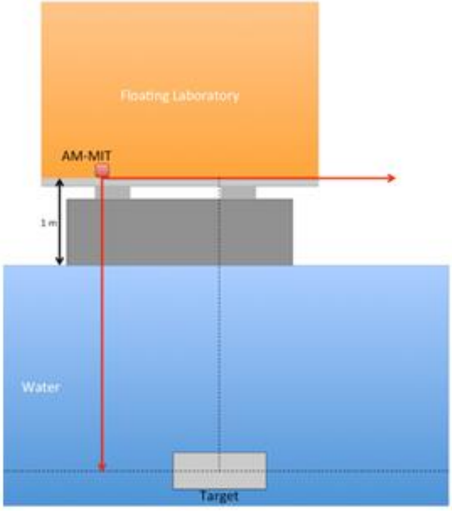

Figure 6 – AMMIT Experimental Setup

The AMMIT device was positioned inside a floating laboratory at Waterlip Quarry. The laboratory has a stainless steel grid below the floor and large steel pontoons. The AMMIT device was able to detect the target through these materials and resulted in the farthest worldwide reported MIT detection range known to date.

This performance equates to target detection at ranges of 10s of metres.

UCL have also demonstrated detection and localisation of underwater targets in a laboratory environment [10] and have reported a reported noise floor of 130fT/√Hz [12] for the device.

3.2 MagCell Project

The Innovate UK funded MagCell project (No. 103999) is a collaboration between Thales UK, The University of Strathclyde, the Fraunhofer Centre for Advanced Photonics and INEX Microtechnologies. The project has developed a magnetometer field demonstrator which exhibits a combination of higher sensitivity and reduced size weight and power compared to existing commercial products

The MagCell magnetometer uses optical pumping and probing of an alkali (Caesium) vapour cell to conduct extremely precise magnetic field measurements.. The Larmor frequency of the spin of the Caesium electrons is proportional to the ambient magnetic field and can be measured by detecting a resonant response to an oscillating perturbation. On resonance a large response is observed in the absorption and polarisation of the coherent laser light passing through the vapour cell.

Within the MagCell a Vertical-Cavity Surface-Emitting Laser (VCSEL) acts as a coherent light source tuned to be resonant with the an atomic hyperfine structure of Caesium. The optical pumping produces a magnetic resonance line width that is dependent on the polarisation and coherence of the sample atomic spins. The MagCell device uses a double-resonance technique which exploits both optical resonance (light resonant with the hyperfine transition, for pumping and probing the sample) and magnetic resonance (RF modulation resonant with Zeeman level splitting) [13]

This double resonance technique results in a versatile sensor capable of measuring both static and alternating magnetic fields to a high degree of accuracy.

The MagCell can be considered as a purely passive device.

The MagCell device is shown in Figure 7.

Figure 7 – MagCell Magnetometer on Optical Bench (top) and On Tripod at Underwood Quarry (bottom)

The MagCell magnetometer is a scalar device which measures only the magnitude of the magnetic field. The Bartington Mag03MSS70 used during testing of the MagCell is a vector magnetometer giving both field strength and direction. The performance of both devices is shown in Figure 8.

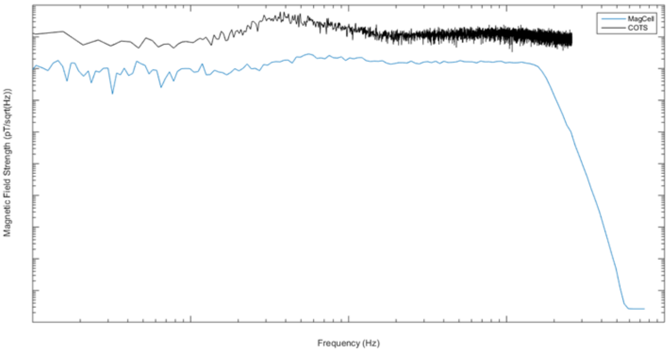

Figure 8 – MagCell Performance Compared to COTS Device

The noise floor of the MagCell device has been measured at 3.4pT/√Hz and an understanding gained throughout the project on how this could be further enhanced.

Thales UK have considered that the MagCell project demonstrator could result in a sensor suitable for remote target detection, classification and tracking.

Initially it could be considered that a vector magnetometer may be better for localisation and tracking of a distant target, however, counter-intuitively it is scalar devices that have been used in magnetic anomaly detection systems.

Vector magnetometers sense both the magnetic field from the target and the ambient (Earths') field, and therefore are highly sensitive to noise in the ambient field, rotation of the array which leads to orientation errors, manufacturing tolerance issues within a single sensor and when producing an array of multiple devices. This means that in practice it is difficult to distinguish the small field produced by the target from the noise floor.

Gradiometers, two magnetometers spaced a known distance apart, can overcome some of the ambient noise issues but manufacturing tolerances potentially still remain. A scalar device such as MagCell is relatively insensitive to orientation other than the two 'dead zones' on the polar and equatorial planes. Outside of these zones it works well over a large number of angles.

Gradiometers are commonly used to measure the gradient of the magnetic field. In measurements over shorter distances this allows for a reduction in false alarm rates. This layout is often used in unexploded ordinance detection or archaeological surveys. For applications where the distance to the target is large, the magnetic field gradient will be small. The sensitivity of the MagCell offers potential for detecting this small change.

A greater benefit would be the reduction in noise that measuring from two sensors offers. Sefati.Markiyeh [14] reports a large increase in signal to noise ratio due to the combined processing of gradiometer data. An example is shown in Figure 8 where the true signal of a passing object is revealed amongst the cluttered raw data.

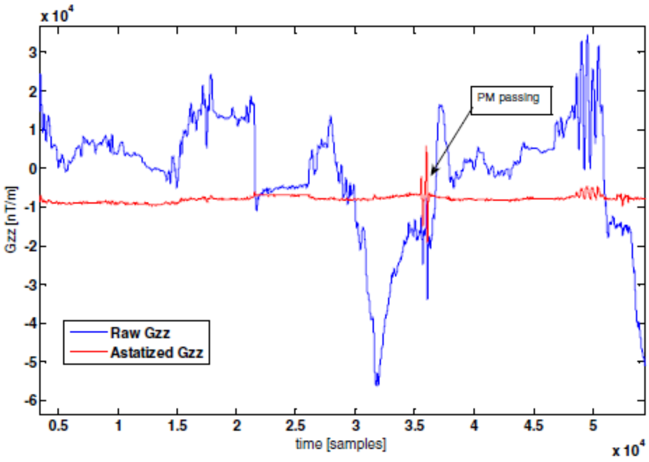

Figure 8 – Gradiometer Response with and without Astatization

Thales UK have used the MagCell device to detect and track a representative target, shown in Figure 9. The mild steel gas cylinder was chosen to represent a Second World War Luftwaffe SC50 Aerial Bomb. Gas cylinders such as these are commonly used within the Oil and Gas industry during seabed surveys for UXO.

Figure 9 – Ferrous Gas Cylinder (Static Magnetic Target) and SC-50 Aerial Bomb

Some results of the testing are demonstrated in Figure 10 and show the total field signature of the gas cylinder as it moves past the MagCell device

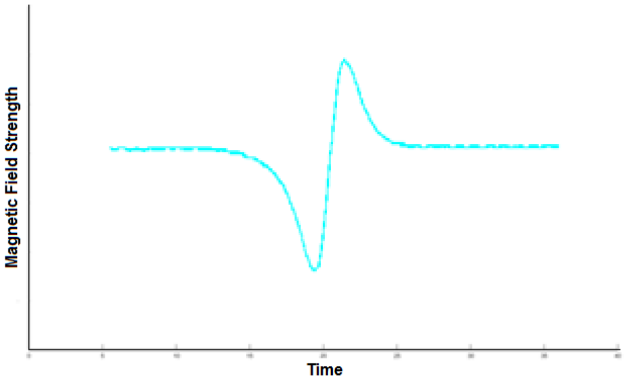

Figure 10 – Total Field Signature of Ferrous Gas Cylinder (Static Magnetic Target)

The results suggest UXOs could be detected at distances of 10s of metres and larger underwater targets at 100s to 1000s of metres. CAE stated a submarine detection range of 1200m using the MAD-XR device with a higher noise floor than the MagCell sensor [16].

In addition to detection of objects, numerous methods have been proposed to track targets with magnetometers by various authors (Zhang [17], Fan [18], Gao [19] and Wang [20] amongst others). An array of MagCell devices would offer an opportunity to put these concepts into practice.

4 Conclusions

There are multiple use cases for the quantum magnetometers within defence applications and those briefly described in this paper cover areas where the main benefits of the sensors will provide the greatest performance enhancements or synergies with current technologies.

Many of the technologies are currently of a low technology readiness levels and developed by academia. Thales UK has investigated two potential devices and, through working in consortiums with academic partners and small to medium enterprises, aided in demonstrating these technologies outside of a controlled laboratory environment.

The detection ranges for UXOs means that magnetometry should be considered for cluttered or otherwise noisy environments such as the surf zone or beaches where traditional techniques are not applicable.

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