7. Bulk Explosive Detection Systems:[15] Nuclear Quadrupole Resonance

7.1 Sensing principle

Operating principle

Nuclear quadrupole resonance (NQR), a derivative of nuclear magnetic resonance (NMR), is a bulk inspection technology which can be used to detect certain chemical elements which have an electric quadrupole moment. Among these is nitrogen-14 (^{14}N) — and nitrogen is a constituent of explosives used in landmines, such as RDX and TNT. NQR has been described as "an electromagnetic resonance screening technique with the specificity of chemical spectroscopy", as it not only detects but can also be used to identify the exact chemical used. Unlike NMR, where a powerful external magnetic field is needed, quadrupole resonance takes advantage of the material's natural electric field gradient, i.e. the electrical gradients available within the asymmetrical molecule itself. These gradients are due to the distribution of the electrical charge; they do therefore strongly depend on the chemical structure and will be different for RDX, for TNT, etc.

When a low-intensity radio frequency (RF) signal of the correct frequency is applied to the material, usually in the range 0.5 to 6 MHz (i.e. slightly higher than metal detectors), the alignment of the ^{14}N nuclei can be altered. After the RF stimulation is removed, the nuclei can return to their original state, producing a characteristic radio signal. The signal can be detected using a radio receiver and be measured for analysis of the compounds present. Detecting the presence of explosives becomes similar to tuning a radio to a particular station and detecting the signal, and the uniqueness of a molecule's electric field allows NQR technology to be highly compound specific. This high selectivity is partly a disadvantage, as it is not straightforward to build a highly specific multi-channel system necessary to cover a wide range of target substances, and the precise frequencies drift with temperature. Coils similar to those of metal detectors are used.

In addition, the signal-to-noise ratio increases with the operating frequency f as $f^{3/2}$, which implies that detection becomes much easier with increasing frequency and hence detection of (low-frequency) TNT is much harder than detection of RDX — for which NQR has already been confirmed as very promising. Care will have also to be taken with the temperature dependency of the spectral lines, selecting for example those

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[15] Bulk explosive detection techniques allow the direct detection of a macroscopic mass of explosive material.

NQR transitions which are least affected by temperature changes (e.g. 3.410 MHz line instead of 5.192 MHz for RDX). TNT also presents further problems due to TNT cast in mines usually being a solid solution of different crystalline forms, which can affect the characteristic frequency response.

Blind tests in the US have demonstrated that NQR is close to readiness for field testing, for use as a confirmation detector for shallow-buried plastic-cased anti-tank mines containing kilograms of explosive. Application for buried anti-personnel mines with only 100g of explosive or less still appears to be extremely elusive for TNT, although research is continuing in several countries.

Application type

Close-in: hand-held (power issues), vehicle-based (especially for anti-tank mines on roads).

Strengths

- NQR is a derivative of nuclear magnetic resonance, which is routinely used, for example, in medical diagnostics, without the need for an external magnetic field.
- NQR technology can be highly compound specific (each explosive has a unique signature).
- NQR has potentially a very low false alarm rate.
- The presence of metallic objects (in particular those containing explosives) can be detected by the detuning effect on the NQR probe.
- NQR is being investigated for other security related applications (e.g. aviation security).
- No nuclear radiation is involved.

Limitations

- Detection times are of a few seconds to tens of seconds, depending on type (in particular relaxation time), quantity and depth of the target substance.[15]
- Impossible to detect substances fully screened by metallic enclosures[16] (also foils, depending on their thickness), e.g. within metal cased mines or UXO. Practical applicability is therefore likely to be an issue which requires extensive testing.
- Detecting TNT is much harder than RDX (because of the frequency dependence of the SNR [signal to noise ratio] and possible presence of two crystalline polymorphs — monoclinic and orthorhombic — which affects the characteristic frequency response and leads to weaker TNT signals).
- Weak signals: signal averaging, shielding and active cancellation of interference, including radio frequency interference, are necessary (the detector must work, in the case of TNT, within the medium wave (AM) radio broadcasting band).

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15. Buried mine detection is a typical one-sided application (the target object can obviously not be put inside a coil as in other applications). The resulting SNR can therefore depend considerably on the target distance, i.e. its depth.

16. It may still be possible to detect explosives in imperfectly shielded objects, e.g. within metallic containers having holes or slots or other regions where there are poor electrical connections (possibly even some UXO), but this will result in a correspondingly weaker NQR signal.

The received TNT signal is so weak that it is often masked by AM radio interference. It is important to know that the TNT response can be recognised even in the presence of high power AM signals. One can obviously not switch off neighbouring AM radio transmitters.

- Spurious signals due to piezoelectric responses from silica in the soil (quartz) and "acoustic ringing" effects (due to certain metals and metal coatings) might require appropriate pulsing sequences and detection software, as well as specific hardware.

Potential for humanitarian demining

- For "confirmation" type of applications.
- Very promising for RDX and tetryl, and/or confirmation of shallow buried plastic-cased anti-tank mines.
- Power requirements are considerable and complicate the design of hand-held equipment.
- Application for small buried anti-personnel mines still appears to be extremely elusive for TNT (unfortunately TNT is much more common than RDX in landmines).
- As electronic systems become cheaper and more powerful it may be possible to substantially improve performance in the future.

Estimated technology readiness

Medium.

Related publications

1. MacDonald J., et al. (2003)
Alternatives for Landmine Detection, RAND Science and Technology Policy Institute, Report MR-1608.
2. Garroway A.N., M.L. Buess, J. B. Miller, B. H. Suits, A. D. Hibbs, G. A. Barrall, R. Matthews, and L. J. Burnett (2001)
" Remote Sensing by Nuclear Quadrupole Resonance", *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 39, No. 6, June, pp. 1108-1118.
3. Bruschini C. (2001)
Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks), ExploStudy, Final Report, Feb. 2001, *http://diwww.epfl.ch/lami/detec/explostudy.html* and *www.eudem.info.*
4. *Proceedings, Expert Workshop on Explosive Detection Techniques for Use in Mine Clearance and Security Related Applications,* 2-4 June 2003, Bled Lake, Slovenia, European Commission, Directorate General Joint Research Centre; International Trust Fund for Demining and Mine Victim Assistance, *http://demining.jrc.it/aris/events/slovenia/PROCEEDINGS.pdf.*
5. Bruschini C., K. De Bruyn, H. Sahli, J. Cornelis (1999)
EUDEM: The EU in Humanitarian Demining - Final Report, July, *www.eudem.info.*
6. Yinon J. (1999)
Forensic and Environmental Detection of Explosives, John Wiley and Sons, 1999, ISBN 0-471-98371-0.

7.2 Quadrupole Resonance Confirmation Sensor: QRCS

Project identification

Project name	Quadrupole Resonance Confirmation Sensor – vehicle-based
Acronym	QRCS
Participation level	National
Financed by	US Army and US Navy (for the Marine Corps) with additional support from DARPA
Budget	Not available
Project type	Technology development Technology demonstration, System/subsystem development

Start date	1997
End date	Ongoing
Technology type	NQR
Readiness level	●●●●●❻○○○
Development status	Ongoing
Company/institution	GE Security (formerly Quantum Magnetics Inc.)

Project description

GE Security asserts that ongoing development efforts will lead to products for both military and humanitarian demining applications. At this point, the manufacturer does not have any landmine detection systems that have reached a prototype stage comparable to the VMR1-MINEHOUND (Vallon/ERA), AN/PSS-14 (CyTerra) or Fido (Nomadics). It does, however, have ongoing programmes to develop mine detection sensors that incorporate quadrupole resonance (QR) detection. Efforts to date have focused on military countermine systems as opposed to humanitarian demining. Projects include a vehicle-mounted system and a hand-held QR/ground penetrating radar (GPR)/metal detector (MD) system. In what follows, the system developed for the detection of anti-tank and anti-vehicle landmines is described.

Detailed description

GE's **Quadrupole Resonance Confirmation Sensor (QRCS)** is meant to confirm or refute the presence of explosives at a candidate location first identified by some other primary sensing device, typically a combination of MD and GPR, thereby providing a considerable reduction in probability of false alarm (>20x) but at a reduced speed to the primary sensor.

The QR coil first acts as a transmitter, irradiating the explosives with a radio frequency (RF) pulse sequence of precise frequency and timing. Then, special circuits remove energy from the QR coil so that it can be used as a low noise receiver. However, the QR coil is unable to discriminate completely between the small signal from the explosive and other interfering signals. The latter are largely cancelled by careful construction of the pulse sequence and minimization of electric fields. The operator of the QRCS receives a simple "clear" signal if no explosive is present, or a warning indicating that either TNT or RDX or a combination of both has been detected [1].

As RDX QR sensitivity is much higher than that of TNT, the key performance limitation is TNT detection. (The nominal signal to noise ratio [SNR] for RDX is 50 times greater than for TNT.) One way of improving the TNT SNR is to increase the scan time, as this increases the relative amplitude of the QR response to the instrument noise. The most successful method is, however, to increase the amplitude of the RF magnetic field used to excite the TNT resonance. Full details are provided in the referenced documents.

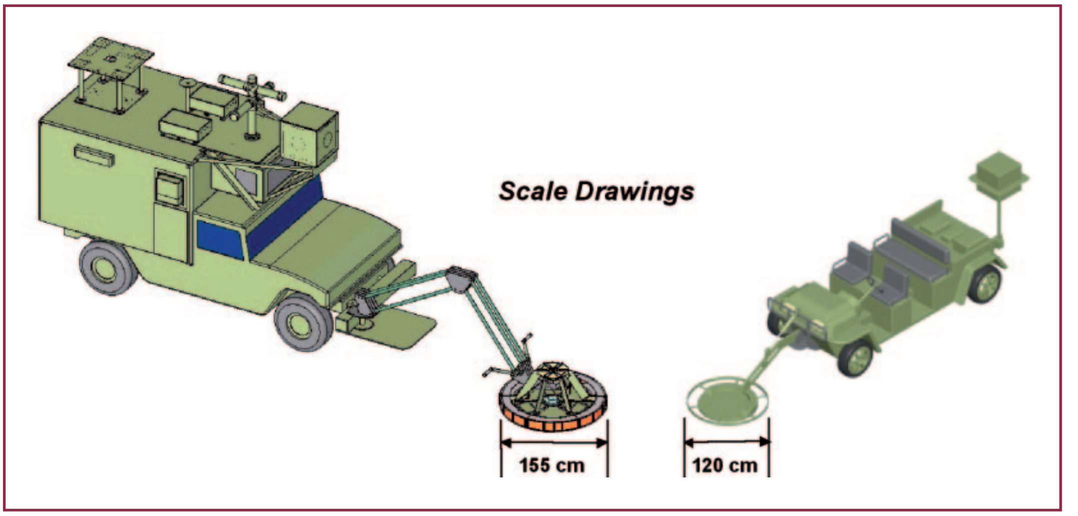

Figure 1. Scale comparison of (left) the original QRCS as tested in 2003 and (right) the next generation QRCS based on developments described in (1).

Test & evaluation

The manufacturer reports [2,3] that during 2002 the QRCS performed in two US government-supervised blind tests. The first test was conducted in an arid environment and the second in a temperate environment. In both tests, locations were marked on the ground over blank sites and sites with a buried mine. The halo or offset from the mark to the edge of the mine was up to 25cm in order to simulate inaccuracy in the location provided by the primary sensor. The distribution of offsets was Gaussian with a 13cm standard deviation and a 0cm bias. The maximum distance to the centre of the mine was ~40cm, assuming a typical anti-tank mine diameter of ~30cm.

The actual halo of the primary sensor may ultimately prove to be smaller than 25cm. The depths of the mines in the arid test were varied with a soil overburden (shortest distance from the soil surface to any part of the mine) ranging from 2.5cm to 12.5cm. In the temperate test, the soil overburden was fixed at 7.5cm. Mines buried at both sites contained either a Comp B (an explosive consisting of ~60 per cent RDX and 40 per cent TNT by weight) or TNT main charge. The mass of the Comp B charges ranged from 2 to 10kg and the TNT charges ranged from 5 to 8kg.

The total scan time at each marker was ~25s. The TNT scans were composed of multiple applications of a short pulse sequence or echo train. The duration of each echo train is of order 100ms with ~5s between echo trains. Both durations are dependent upon the estimated temperature of the explosive. The trialled system performed the entire 20s

TNT scans (~4 echo trains with 5s between each), followed by a 3-6s RDX scan. Simple modifications to the system are possible to implement the RDX scan between the individual TNT echo trains.

The 2002 blind test results were presented as follows [2,3]:

Table 6 . QRCS System-2002 blind test results

Test Location	PD (90% confidence limit)	PFA (90% confidence limit)	# of markers
Arid Test Site	0.98 (0.95, 1.00)	0.04 (0.02, 0.07)	312
Temperate Test Site	0.98 (0.90, 1.00)	0.04 (0.02, 0.10)	134

The manufacturer reports that since then it has implemented methods to improve radio frequency interference (RFI) immunity due to the presence of large RF interference in the frequency bands of interest, as well as to cancel piezoelectric ringing generated in the very near field of the QR coil. Further tests were carried out in 2003 at the same test site as in 2002, under largely similar conditions although temperatures were slightly higher and the scan time was approximately 29s.

The 2003 blind test results were reported as confirming "exceptional RDX performance", with an overall performance which was nearly identical night or day, but with a TNT performance well below that demonstrated in 2002 [1]. This was due to the improvements in ringing rejection and RFI immunity, which reduced the TNT sensitivity per unit time. Reversing this effect is achieved most simply by increasing the scan time. It is reported that further technical improvements during 2004, such as the increase in the peak excitation field for TNT, which resulted in an approximately twofold increase in TNT SNR per complete scan, restored the TNT sensitivity [1].

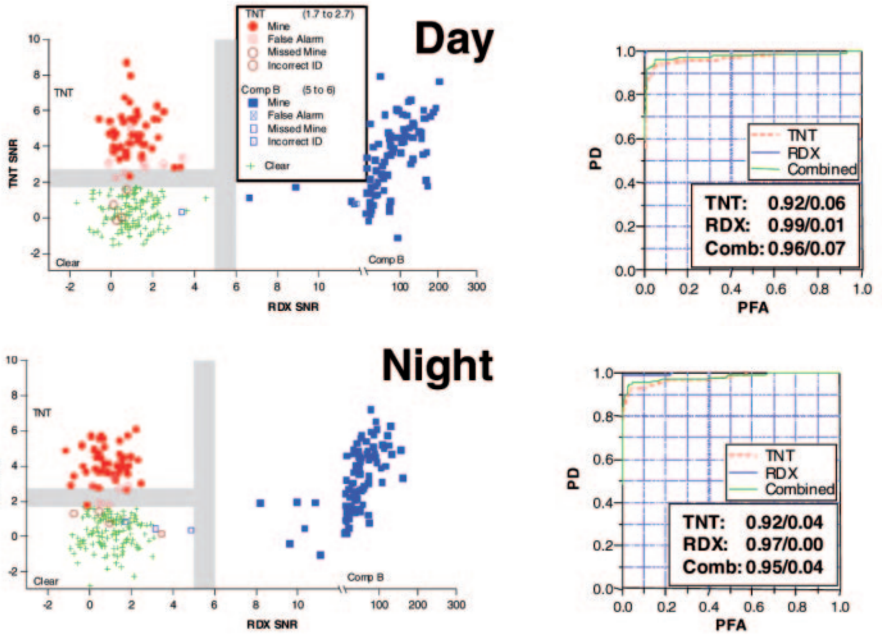

Figure 2. Arid test site results in 2003 (1). (Left) TNT and RDX signal amplitudes for blanks, Comp B mines and TNT only mines. (Right) Associated ROC curves with sample PDs and PFAs listed for TNT, RDX and Combined detection. (Top) Daytime results. (Bottom) Night-time results. The gray bars on the left plots indicate the rescan threshold range.

Other applications (non-demining)

Security applications, e.g. baggage screening.

Related publications

1. Barrall G.A. et al. (2005)
   "Advances in the Engineering of Quadrupole Resonance Landmine Detection Systems", *Proceedings of SPIE Conference on Detection and Remediation Technologies for Mines and Mine-like Targets X,* Vol. 5794, pp. 774-785, Orlando, US.
2. Barrall G.A. et al. (2004)
   "Development of a Quadrupole Resonance Confirmation System", *Proceedings of SPIE Conference on Detection and Remediation Technologies for Mines and Mine-like Targets IX*, Vol. 5415, pp. 1256-1267, Orlando, US,.
3. Barrall G.A. et al. (2004)
   Nuclear Quadrupole Resonance for Landmine Detection, Military Sensors Symposium in Dresden, Germany.
4. Williams C., P. V. Czipott and L. J. Burnett (2001)
   "Quantum Magnetics Targets Landmine Explosives Using Quadrupole Resonance", *Journal of Mine Action*, Issue 5.2, August 2001, *http://maic.jmu.edu/journal/5.2/features/quantum.htm.*
5. Garroway A.N., M.L. Buess, J.B. Miller, B.H. Suits, A.D. Hibbs, G.A. Barrall, R. Matthews, and L.J. Burnett (2001)
   "Remote Sensing by Nuclear Quadrupole Resonance", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 39, No. 6, June 2001, pp. 1108-1118.

Technical specifications	*GE Infrastructure QRCS*
1. Used detection technology:	NQR
2. Mobility:	Vehicle-based
3. Mine property the detector responds to:	Explosive content in bulk form
4. Detectors/systems in use/tested to date:	—
5. Working length:	Not applicable
6. Search head:	
➢ size:	Diameter: 120cm, height: 10cm.
➢ weight:	QR coil: 13kg
➢ shape:	Circular
7. Weight, hand-held unit, carrying (operational detection set):	—
Total weight, vehicle-based unit:	63kg
8. Environmental limitations (temperature, humidity, shock/vibration, etc.):	Typical military requirements.
9. Detection sensitivity:	Targeted at kg quantities of explosives with up to 20cm overburden.
10. Claimed detection performance:	—
➢ low-metal-content mines:	N/A
➢ anti-vehicle mines:	PD: >95%, PFA: <5%.
➢ UXO:	—
11. Measuring time per position (dwell time):	20-30s
optimal sweep speed:	—
12. Output indicator:	Yes(TNT, RDX or both)/No signal
13. Soil limitations and soil compensation capability:	Induced piezo-electric ringing (esp. from quartz).
Soil compensation:	Employs modified pulse sequences and minimization of electric fields (e.g. use of reference antennae).
14. Other limitations:	Environmental radio frequency interference (power lines, AM transmitters). Residual coil and electronics ringing. Temperature variations (induces changes in resonance frequencies).
15. Power consumption:	<200W during 20s scan, <40W when idle. Average: 120W.
16. Power supply/source:	4 car batteries or 8 NiMH batteries.
17. Projected price:	—
18. Active/Passive:	Active
19. Transmitter characteristics:	Peak transmit field: 16 Gauss, peak transmit power: 21kW (both in TNT mode).
20. Receiver characteristics:	—
21. Safety issues:	None
22. Other sensor specifications:	Overall system volume: ~0.35m^3.

Remarks

These specifications refer to the low size, power and weight system currently under development (next generation QRCS system (1)).

Key performance limitation is TNT detection.