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ADVANCED METHODS OF DETECTING EXPLOSIVES IN IMPROVISED EXPLOSIVES DEVICES

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Review article

Abstract: Bomb disposal squads who identify and test improvised explosives devices and ordnance mostly use dogs, metal detectors, traditional detectors of trace particles and portable X-ray devices. Magnetometers and ground-penetrating radar devices are used to find ordnance under the ground, and sonar is used to find ordnance under water. In some cases, however, it would also be appropriate to make use of certain advanced methods of detecting explosives, such as quadrupole resonance, neutron in - gamma out, and optical methods of stand-off detection.

Keywords: IED, EOD - Explosive Ordnance Disposal, Explosives, QR, Neutron in - Gamma Out, Stand-off Optical Detection.

Introduction

It is very technically challenging to find improvised explosives devices (IEDs) in buildings, on premises, on streets, etc. It is usually dogs which have been specially trained to find sources of explosives vapours using their excellent sense of smell which provide initial indications when looking for explosives during one-off security checks of various spaces. This is not because trace particle detectors are not sufficiently sensitive. Their shortcomings in security checks of various spaces compared to dogs are the following: Slower sampling on site and more risky for the person, with analysis also usually somewhat slower, they do not detect or process useful information given by accompanying smells, they are not currently particularly well-developed in terms of processing the intensity of signals in various places in order to estimate the vapour source (an exception here is, e.g., the LOTUS project[3]), the preparation time prior to measurement (heating, washing, etc.) is also often longer, there are requirements in terms of physical measurement conditions, and there are sometimes also shortcomings in terms of dimensions, weight, battery capacity and electricity dependence (Tureček, 2013a). Most of these parameters are continuously improving for explosives detecting equipment, but dogs will remain hard to replace for a long time to come in these types of checks. In cases of security checks of persons, luggage, consignments and vehicles, the situation is more favourable for the equipment. Practically all the above listed weaknesses no longer apply, or do not matter. And the main advantage of equipment remains - determining the type of explosive. In contrast, for dogs their main weakness becomes very evident - their inability to work 24 hours a day, seven days a week. Considering that dogs can work continuously for a maximum period of around 20 minutes (Lichorobiec, 2014), dogs are only suitable for higher levels of mass security checks on persons and their luggage. Dogs, then, are an excellent means for finding explosives in one-off security inspections of various premises. In certain cases, such searches using dogs should

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[3] The LOTUS (Localisation of Threat Substances in Urban Society) project is a European research project focused on detecting the vapours produced during the making of home-made explosives. The proposed mobile detection devices, possibly complemented by a stationary network of detection devices, are designed to detect the vapours produced in the manufacture of explosives within the inspected area, and then determine the approximate location of the source by measuring their concentrations at various places and considering wind direction, and then possibly further specify this location through laser stand-off detection (Tureček, 2018a).

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be combined with certain equipment. Here, these pieces of equipment are mainly used for the further investigation of suspicious objects.

Results

Detecting mines and unexploded ordnance

Different instruments are suitable for detecting mostly mines and unexploded ordnance on the land above ground or underground, or under water. Most commonly these include metal detectors, detectors of magnetic anomalies in the Earth's field (magnetometers), ground-penetrating radars, and sonars for underwater detection. Nonlinear transition detectors are also used in detecting IEDs on the ground. A lot of experience is required in order to achieve the necessary professional level when working with metal detectors, magnetometers and nonlinear transition detectors. Specialist and experienced personnel are required in order to interpret soil-penetrating radar and sonar images. It is not normally worth it for bomb-disposal teams to employ such narrowly-specialised ground-penetrating radar or sonar staff. Instead, they prefer to hire private companies for specific jobs.

The signal produced by metal detectors is caused by the electromagnetic induction of eddy currents in conductive materials, i.e. in particular in all metals, and/or changes in the orientation of magnetic domains in ferromagnetic metals. Magnetometers measure non-homogeneity in the Earth's magnetic field caused by the proximity of large bodies of ferromagnetic material (Schüler, 2000). Ground-penetrating radars transmit short high-frequency electromagnetic pulses. The speed they are transmitted is given by the electric and magnetic properties of the surroundings - permittivity, permeability and resistivity. Reflections and refractions occur at the interface of different materials (Daniels, 2010). Nonlinear transition detectors detect the presence of nonlinear transitions, these mainly representing semiconductor components. These are contained in practically all electronic components (Tureček et al., 2014). It is clear from these physical principles that explosives are either not detected at all, or are only detected as a mass of essentially unspecified material, using these methods. These methods detect the IED as a whole unit. The actual explosives are not detected. It is rather the other parts of the IED which are detected, such as detonators, cables, batteries, switches and the metal components often included to increase IEDs' destructive effect. For ordnance, it is metal components which are mostly detected. Here a fundamental problem arises where IEDs or ordnance, such as certain landmines, contain only a small amount of metal components. In such cases, nuclear quadrupole resonance would seem appropriate.

Nuclear electric quadrupole resonance (Quadrupole Resonance, QR) uses radio waves to detect certain volumes of particular types of explosives or drugs, regardless of their distribution within the checked space. In terms of excitation and excited radiation, these instruments are similar to metal detectors, and in terms of the way they are designed and their security application they are also similar.

In nuclear quadrupole resonance, the transmitter sends a complex pulse of low intensity radio waves into the luggage area. The original rest rotation axis orientation of the atomic nuclei of the substance being examined is disrupted by this pulse. As the nuclei then endeavour to recover, they produce a particular characteristic radio signal which is typical for the specific substance. This signal is captured by the receiver and immediately analysed by a computer. These instruments often look for elongated nuclei of the N-14 nitrogen atom located in explosives, or else for chlorine. It is very important to realise that the surrounding atoms slightly shift the resonance frequency. The size of this shift depends on the type of environment, and we can use this fact to deduce what type of molecules are involved, and so what substance it is - whether it is pentaerythritol tetranitrate (PETN), hexogen (RDX), and so on. QR is a highly specific method because its sensitivity depends on the shape of the molecules (Turecek et al., 2012).

Quadrupole resonance is, like X-ray systems, a typical volumetric explosives detection method. In this case, insulation in front of sublimed or vaporised explosives particles or in front of surface luggage contamination, does not matter for, in this case, the detection of explosives volume. In certain situations, it can be an advantage that a small amount of explosives does not result in a signal. The likelihood of a false positive detection is minimal for QR, and the method detects the specific substance involved. Furthermore, the precision of the finding increases as the measurement time increases. It can detect substances anywhere within the object being inspected regardless of its orientation and distribution. The explosives may be shaped into thin combs or, importantly, separated into smaller parts, etc., but they will still be detected. They key factor is the total number of molecules of interest within the area being inspected. Any metal will, of course, shade the exciting and excited quadrupole

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resonance signal. Even so, these instruments are capable of detecting explosives even when partially shaded by metal. Furthermore, these instruments often also include a metal detector function which warns of the presence of dangerous shading by metals (Tureček, 2017c).

Detecting IEDs in body cavities

When discussing the options for using quadrupole resonance for bomb disposal purposes, the fact that quadrupole resonance is indispensable for finding IEDs in body cavities should be mentioned. The smuggling of contraband, mainly packages of drugs, is a long familiar problem for customs officials the world over, mainly at airports. The idea of IEDs in body cavities may appear improbable in contrast, but it has already happened. Al-Queda, specifically Abdullah Hassan al-Asiri, attempted to commit a suicide bombing on Saudi Arabia's Interior Minister and member of the Royal Family, Muhammad bin Nayef. It is estimated that he had around 100 g of PETN plastic explosive in his anal canal, including a triggering mechanism, probably with a mobile, which was likely set off when the attacker repeated a phrase. Luckily, the suicide attacker's body significantly dampened the effects of the explosion, and Muhammad bin Nayef was only slightly injured. We need to consider the possibility of IEDs in body cavities.

X-ray full body scanners face issues in most countries in regard to their approval for use in security checks of passengers at airports, even though there is little justification for such issues.

In future, terahertz reflection spectroscopy appears ideal for determining the type of material located under someone's clothing, and in the even further future, active terahertz tri-dimensional imaging of reflected radiation from every spatial point of the inspected area could be utilised. The penetration of terahertz irradiation of human tissue, which contains lots of water molecules which strongly absorb terahertz radiation, however, is poor (Tureček, 2009; Yinon, 2007).

It would appear, then, that only the nuclear quadrupole resonance (QR) method remains for detecting explosives and drugs hidden in passengers' body cavities, alongside Nuclear Magnetic Resonance (NMR) sister techniques which do not need a strong stationary magnetic field. It should be noted, however, that QR is not suitable for detecting liquid explosives (Tureček, 2008; Yinon, 2007). Their use in body cavities would, however, be complicated. These instruments may take the form of gates and hand-held devices, similar to metal detectors. These gates and hand-held detectors will also work as metal detectors. The instruments will also naturally detect explosives and metal objects hidden under or in passengers' clothing (Tureček, 2017b). In contrast to metal detectors, the detection of explosives using quadrupole resonance will not be accompanied by the people undergoing checks constantly having to remove and show harmless items in their pockets.

Portable X-ray systems as the basis for examining suspicious objects

Once a suspicious object is found that may contain an IED, it is usually examined using a portable X-ray system. If possible, the suspicious object is not moved, and a source of X-ray radiation, the X-ray tube, is placed at one of its sides, with a detector of the X-ray radiation which has passed through the examined object on the opposite side. Panels with detection elements made of semiconductors or scintillators with photodiodes, or very thin panels containing an electroluminescent or photographic material are usually used for X-ray detection. This latter group is suitable for bomb disposal use because the very thin cassettes (panels) can be inserted into small gaps, for example between a suspicious waste-bin and a wall, allowing you to produce an image in the required direction without having to move the bin. These lack a lot of other technical options, however. Panels with detection elements are better when the dual energy method is used for imaging, a method already used. Without using dual energy photon X-ray display, it is almost impossible to guess the type of materials (Tureček, 2013b). Using dual energy methods, materials on the image can be differentiated into organic, inorganic and metal material groups. Even using a dual energy method, however, it is impossible to determine whether the particular organic material is dangerous (e.g. an explosive) or a chemical poison, or whether it is a harmless organic material, e.g. paper, plastic, type of food, etc. (Tureček, 1998). The bomb squad rely on IEDs being revealed through secondary indications on the X-ray image. These might include a detonator shape pushed into the organic material, contact wires or a plastic tube (Nonel tube) leading from the detonator to some other initiating component (e.g. electronics), the presence of a connected battery, etc. The X-ray image provides excellent information essential for various methods of disabling the IED. They are often used to measure the shaped charges for detonating the IED. Examples of these methods of disabling IEDs are given in detail in relevant publications, e.g. (Lichorobiec, 2011; Lichorobiec and Figuli, 2017).

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Need for volumetric methods of detecting explosives in IEDs

Portable X-ray systems thus do not allow us to determine whether the organic material in the examined material is an explosive or not. This can result in a number of problems. There have been cases in history where a suspicious object was detonated using a directed charge, and the detonation led to significant material damage. It was then shown subsequently that the suspicious object did not contain an IED or any other explosive material. On the other hand, an even more serious error can occur where the X-ray image of a suspicious object does not show any object within the organic matter, leading to the conclusion that there is no detonator there. Unfortunately, invisible detonators can be set up, where the detonator cannot be seen on X-ray images. More specifically, these are detonators which blend in perfectly with the surrounding explosive due to the same effective atomic number of their components and the particular explosive (Tureček, 2006).

The assumption that the examined suspicious object does not contain any explosives where this assumption is based only on the negative detection of trace particles by a dog or an instrument represents a danger. Explosives can be perfectly insulated within an IED (Tureček, 2006). Because this type of insulation is physically and technologically complex, it is luckily not very likely in security practice although it cannot, however, be ruled out.

Portable instruments based on nanosecond neutron analysis (NNA) with the detection of associated particles (API) appear to be suitable for the detection of explosives in IEDs.

Need for volumetric methods of detecting chemical poisons in IEDs

Neither do portable X-rays allow bomb disposal squads to determine whether the organic matter in the examined object is a chemical poison or not. Radioactive materials, a traditional component of dirty bombs, give off gamma rays, which penetrate matter easily, including any metal IED containers, and can be easily detected by instruments. Furthermore, radioactive material appears as a highly absorbing material on the X-ray image. Options for disabling dirty bombs are well described in publications (Lichorobiec, 2009). In contrast to this, a positive instrument detection of chemical poison trace particles near an IED need not necessarily mean that the IED does actually contain that chemical poison. While such a positive detection is a strong indication, it may only be the surroundings or surface of the IED which are contaminated with the chemical. There is a much greater danger if it is assumed that the particular IED does not contain any chemical poison where this assumption is purely based on the negative detection of trace particles. This is because chemical poisons can also be perfectly insulated within the IED (Tureček, 2006). Portable instruments based on nanosecond neutron analysis (NNA) with the detection of associated particles (API), one of the neutron in - gamma out measurement methods, appear to be suitable for the volumetric detection of chemical poisons in IEDS.

Neutron in - gamma out methods for volumetric detection of explosives in IEDs

Using neutron methods, the examined object is irradiated with a flow of neutrons, also called neutron radiation. Either scattered neutrons, or, in particular, gamma radiation emitted by particles in the material being examined following collision with neutrons are detected. Various chemicals occurring within the material being examined produce gamma radiation of various wavelengths characteristic for the particular chemicals following the scattering or absorption of the incident neutrons. By separating out the distribution of the measured gamma ray spectrum we can get the material's elementary composition with the relative proportions of individual elements, i.e. the empirical formula of the substance, thus determining the explosive type. The main benefit of this group of methods is its high penetration capability. The explosive can be detected even if it is hidden in a steel container or behind walls made of concrete, metal or other materials. At the same time, we can also use it to detect and specify safe chemicals and biological substances. A portable device based on Nanosecond Neutron Analysis combined with Associated Particles Imaging Fappears to be the most advanced and most appropriate option for bomb disposal squads. The NNA method is based on the Pulsed Fast Neutron Analysis (PFNA) method.

Pulsed Fast Neutron Analysis

Pulsed fast neutron analysis involves the irradiation of the examined object (e.g. an item of luggage) using fast neutrons over a fixed time period (given, for example, by the pulse operation of the neutron source) followed by the detection of gamma radiation as the product of the inelastic scattering of neutrons on the nuclei of light elements (carbon, nitrogen, oxygen, etc.). The pulse operation

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allows time information to be used (conformance or non-conformance of measurements) to activate gamma detectors during short intervals only, according to neutron source timing. This can be extremely useful in reducing unwanted background effects.

By using information on the neutron time of flight (TOF), we can determine the position of the detected material within the inspected volume, because both the speed of the neutron and the speed of the gamma radiation are known in principle. The starting signal for measuring the gamma radiation is given by each neutron pulse, while the end signal is given by the actual gamma detector (gamma rays move at the speed of light - much faster than neutrons). If this is combined, for example, with vertical scanning of the object being examined using a neutron ray while also moving the object being examined horizontally in a direction perpendicular to the scanning plane, the pulses produce a three-dimensional spatial image of the object being examined. Resolving power is then given in spatial elements known as voxels. The type of material is again determined by spectroscopy of the detected gamma radiation (Marshall and Oxley, 2009; Turecek, 2017a; Yinon, 2007).

Associated Particles Imaging

The method of displaying associated particles is a Pulsed Fast Neutron Analysis (PFNA) variant which also includes the detection of associated alpha particles produced in the neutron generator. This method exploits the fact that the source emits one alpha particle along with every fast neutron, at an angle of 180° (i.e. in the opposite direction). These alpha particles can be registered within the generator using detectors differentiating the point of impact. These register both the moment of alpha particle generation (and so also the accompanying neutron), and also the relative direction in regard to the source (and so also the direction of the accompanying neutron, since its direction of movement is the opposite of the direction of movement of the alpha particle). As such, this once again represents TOF technology (measuring the time of flight) as described in the chapter on PFNA. This allows us to determine the distance the neutron travels until collision. Because we also know the direction of the neutron's flight, this method can in principle provide a spatial, three-dimensional image without the need for scanning, as required in PFNA. The type of material in each voxel (volume element) of the space being inspected is again determined using gamma spectroscopy. Thus, the associated particles imaging method is able to provide a three-dimensional image, voxel by voxel, of the chemical composition of the object being investigated (Turecek, 2017a; Vakhtin et al., 2006).

Nanosecond Neutron Analysis

Nanosecond neutron analysis is the latest attempt at perfecting PFTNA and Associated Particles Imaging technology in order to exploit nanosecond time information to create a three-dimensional image of the distribution of elements within an inspected object. Nanosecond Neutron Analysis is based on irradiating the inspected object with fast neutrons and detecting secondary gamma radiation within a narrow (nanosecond) time period measured in relation to the associated particle. This allows for the detection of a small amount of explosive hidden in the middle of a large amount of non-explosive material (Turecek, 2017a; Vakhtin et al., 2006).

Cutting edge bomb disposal squads should have a portable instrument based on Nanosecond Neutron Analysis (NNA) and Associated Particles Imaging (API) available to them so that they can undertake a volumetric analysis of the organic content of containers with thick metal walls. In the event of an ambiguous result for an X-ray image and trace particle sampling, this neutron method can be used to either confidently rule out the presence of a large dangerous amount of explosives, even where there is surface contamination of the container with explosives, or instead detect the presence of a large amount of explosives. In the event of a positive detection, the operator will have information available to them about the type of explosive, its total amount and its spatial distribution within the inspected object. Where terrorists use a combination of an IED with chemical or biological agents, NNA with API is also indispensable for examining thick walled containers in particular. In addition to ruling out or detecting explosives, it also rules out or detects the presence of a particular amount of these other dangerous substances, including displaying their spatial locations, and determining their empirical formula. As well as in IEDs, this capability could also be applied in detecting and analysing old chemical munitions, such as those dating back to the First World War. NNA with API is also indispensable for bomb disposal squads in cases where the IED is buried, walled in or in concrete, etc, and access to its possible position is only from one side.

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Stand-off detection of bulk charges

The detection and disposal of bulk IED charges is a major problem (Lichorobiec, 2010). For safety reasons, there is a need to detect the possible presence of bulk IED charges from a sufficient distance. Bulk IED charges used by terrorists are typically IEDs located in vans or trucks. This is usually necessary due to the logical need of transport to the scene of the crime. We can, however, exploit simple facts and assumptions. A few tons of explosives on a lorry will sublime a large stream of vapour from the explosives. Additionally, the limited opportunities for "home-made" IED manufacturing mean we can assume that the insulation of this vapour will be far from perfect, and quite likely completely absent. Similarly, we can assume that the surface of the lorry will be significantly contaminated with explosives residue. This would imply we can directly detect trace particles.

We can detect explosives trace particles either using a traditional sample collection method, or using stand-off optical methods. The collection of samples can be undertaken either by collecting vapours from around the object being inspected, or through a swab of explosives residue from the surface of the object being inspected. We are now interested in detecting explosives trace particles using stand-off optical methods, ideally from a large distance. In stand-off optical methods of explosives detection, it is mainly lasers that are used as a source of radiation. Lasers offer new ways to detect explosives which cannot be used with other techniques. Some of the promising and rapidly developing methods of optical explosives detection include infrared spectroscopy, Raman spectroscopy (these two comprising the vibrational spectroscopy group) and laser-induced breakdown spectroscopy.

Vibrational spectroscopy

Vibrational spectroscopy is a term used for two analytical methods - infrared spectroscopy (IR) and Raman spectroscopy. These techniques measure the vibrational energy levels which relate to the chemical bonds of the sample (Fuchs et al.,2012; Tureček, 2018b).

Laser-induced breakdown spectroscopy

Laser-induced breakdown spectroscopy (LIBS) is a method of atomic emission spectroscopy. In this method, the sample is irradiated with a short but powerful laser pulse which turns the sample particles within a tiny area into a microplasma. Some of the excess energy is released in the form of photons of light. Through spectral analysis of the emitted light, we can determine the concentration of individual elements within the sample (Tureček, 2018b; Wallin et al., 2009).

Other methods using lasers are also being investigated for use in detecting explosives.

Conclusion

Bomb disposal squads who identify and test IEDs and ordnance mostly use dogs, metal detectors, traditional detectors of trace particles and portable X-ray devices. Magnetometers and ground-penetrating radar devices are used to find ordnance under the ground, and sonar is used to find ordnance under water. In some cases, however, it would also be appropriate to make use of certain advanced methods of detecting explosives, such as quadrupole resonance, neutron in - gamma out, and optical methods of stand-off detection.

In order to detect IEDs or ordnance, such as certain landmines, which contain only a small amount of metal components, instruments which are based on nuclear quadrupole resonance are suitable. Quadrupole resonance can also be used to detect IEDs within body cavities.

Cutting edge bomb disposal squads should have a portable instrument based on NNA and API available to them so that they can undertake a volumetric analysis of the organic content of containers with thick metal walls. In the event of an ambiguous result for an X-ray image and trace particle sampling, this neutron method can be used to either confidently rule out the presence of a large dangerous amount of explosives, even where there is surface contamination of the container with explosives, or instead detect the presence of a large amount of explosives. In the event of a positive detection, the operator will have information available to them about the type of explosive, its total amount and its spatial distribution within the inspected object. Where terrorists use a combination of an IED with chemical or biological agents, NNA with API is also indispensable for examining thick walled containers in particular. In addition to ruling out or detecting explosives, it also rules out or detects the presence of a particular amount of these other dangerous substances, including displaying their spatial locations, and determining their empirical formula. As well as in IEDs, this capability could also be applied in detecting and analysing old chemical munitions, such as those from the First World War.

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Bulk IED charges, typically located in lorries, need to be detected from a sufficient distance. We can assume that for bulk IED charges in lorries, the explosives will in all likelihood be poorly insulated, and a few tons of explosives will result in a relatively large flow of vapour escaping from the explosives. The surface of the lorry may also be contaminated. Optical methods can detect explosives particles from a distance of up to around 30 metres.

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