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Latest Trends in MASINT Technologies for CBRNe Threats

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Abstract:

The article provides up-to-date information on the latest Measurement and Signature Intelligence (MASINT) technologies to face Chemical, Biological, Radiological, Nuclear and Explosive (CBRNe) threats and their advancements exploitable by Intelligence and security practitioners. The primary emphasis is on CBRNe technologies, given their central role in MASINT. The discussion encompasses cutting-edge developments that exhibit significant potential in enhancing capabilities for the identification and mitigation of CBRNe risks. In addition, the document puts forth a set of recommendations which cover essential improvements and approaches to effectively address various aspects of CBRNe Intelligence. This comprehensive exploration aims to provide readers, including Intelligence and security practitioners, with valuable insights into the evolving landscape of MASINT technologies addressing the unique challenges posed by CBRNe threats.

Keywords:

CBRNe, MASINT, intelligence, security, technologies

1 Introduction

In 1996, a senior Intelligence official stated that Measurement and Signature Intelligence (MASINT) could support military operations, as well as provide Intelligence relevant to defense acquisition, arms control, and treaty monitoring, counter-proliferation and counter-narcotics, and environmental monitoring [1]. The purpose of this review article is to offer an overview of the most relevant technologies available today and their capacities to support MASINT discipline. Therefore, the article makes a thorough review and categorization of solutions for MASINT Intelligence tasks. As an Intelligence discipline, MASINT deals with a set of quite specific types of threats from which security and defense forces need to protect the citizens. This article is specifically dedicated to technologies that support the detection, identification, and

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sampling of Chemical, Biological, Radiological, Nuclear and Explosive (CBRNe) threats within the MASINT discipline, such as those focused on infrared, optical, and nuclear radiation, materials, and Multi- and Hyperspectral Imagery.

In the report, we present technologies for fighting both CBRN threats and explosives (CBRNe). Despite the fact that explosives were used in most of the massive terrorist attacks in recent years, for example the "11M" attacks in Madrid, the majority of European countries' legislations do not include explosives in CBRN risks and threats. According to the study *CBRN Integrated Response Italy* [2], only France and the Netherlands consider explosives as part of the regulation of CBRN hazards. However, explosives are a substantial part of the so-called "dirty bomb". The above-mentioned study recommended the inclusion of explosives, "e" factor, as part of the CBRNe legislation and related normative to raise legal framework comprehensiveness and reduce legal uncertainties. In addition, the Geneva International Centre for Humanitarian Demining (GICHD) has released the Improvised Explosive Device Clearance Good Practice Guide in 2021 [3], whose Chapter 5 is devoted to providing basic information on the chemistry of explosive substances, both military/industrially manufactured explosives and on Home-Made Explosives (HME).

The research article is structured as follows. The first section provides an overview of MASINT technologies and CBRNe threats. The second section describes both current and promising MASINT technologies for detection, identification, and sampling of CBRNe. The third section offers several discussions on the adoption of MASINT technologies, as well as recommendations on topics for further analysis for security Intelligence. The conclusion summarizes the key findings of the article.

2 Overview of MASINT Technologies and CBRNe Threats

The concept of MASINT as an Intelligence discipline is much more recent than other disciplines, such as Imagery Intelligence (IMINT) and Signal Intelligence (SIGINT). It includes a set of different collection and analysis activities. The acronym MASINT was first coined in the 1970s by the Defence Intelligence Agency (DIA), and the United States (US) Intelligence community first classified MASINT as a formal intelligence discipline only in 1986 [4]. The North Atlantic Treaty Organization (NATO) document *NATO Glossary of Terms and Definitions* defines MASINT as "*Intelligence derived from scientific and technical analysis of data obtained from sensing instruments for the purpose of identifying any distinctive features associated with the source, emitter, or sender, to facilitate the latter's measurement and identification (2013-10-31)*" [5]. As an Intelligence discipline, MASINT runs through the Intelligence Cycle and the Joint Intelligence Surveillance and Reconnaissance (JISIR) process [6], and addresses quite specific threats with a particular focus on those technologies that support the detection, identification, and sampling of chemical, biological, radiological, nuclear and explosive (CBRNe) threats through infrared, optical, multispectral and hyperspectral imaging measurements [7].

Among the list of threats, the risk of terrorist actions involving the use of offensive CBRNe, including those of low technical complexity, is the subject of constant concern and discussion. Although it is true that their use in terrorist actions has not been very frequent, there are examples that are worth paying attention to this type of threats even if these attacks materialize with less frequency than *conventiona*l terrorist actions. The proliferation and risk of use of CBRNe, known as Weapons of Mass Destruction (WMD), represents a serious threat because these weapons have an enormous destructive potential and a largely indiscriminate impact force and can be used not only in wartime, but "*CBRN incidents have also included accidental releases during peace time operations, and many of the principles for CBRN incident response can be applied to other Hazardous Material (HAZMAT) incidents*" [8].

The different MASINT technologies used in the detection, analysis, identification, and monitoring activities of CBRNe threats provide different capacities also based on the operating range – close and far. Moreover, the sensors can be placed in a variety of platforms, sub-surface, ground, marine, and aerospace platforms. Regarding the CBRNe threat, according to the US Army FM 2-0 Intelligence Manual [9], the most appropriate MASINT technologies and sensors for CBRNe threat and risk detection are: (1) *Devices based on infrared (IR) and optical technologies* which are available for both close and far operating ranges. The collection, processing, exploitation, and analysis of energy emitted or reflected in the range of optical, ultraviolet, visible, and infrared radiation allow the use of MASINT means and sensors, radiometers, spectrometres, lasers, Light Detection and Ranging (LIDAR), etc., for the detection of CBRNe threats or risks. (2) *Devices based on nuclear and radiological technologies* can be used in both operating ranges and provide information on nuclear radiation and other physical phenomena related to nuclear devices – weapons, reactors, materials, etc. (3) *Devices based on materials technologies* – gas, aerosol, vapor, liquids, solids – are suitable only in close operating range.

The collection and processing of signatures and signals of different products, solids, liquids, or gases susceptible to be used to produce aggressive CBRNe is vital for the fight against this risk and threat. The permanent updating of signatures and signals of samples of materials and products likely to be used, alone or in combination with others, as a CBRNe threat is a permanent task. (4) *Devices based on multispectral (MS) and hyperspectral (HS) imagery technologies*. MS imaging – till 10 bands – is only suitable in close range, while HS imaging – till 1 000 bands – is suitable in close range and truly useful in far range. According to the reference Hyperspectral Imaging (HSI), "*Many remote sensing tasks which are impractical or impossible with an MSI system can be accomplished with HSI. For example, detection of chemical or biological weapons, bomb damage assessment of underground structures, [...] are just a few potential HSI missions*" [10]. An example of MASINT technology based on HS resolution is the Hyperspectral Precursor of the Application Mission (PRISMA) [11].

According to the Final Report of National Security Commission on Artificial Intelligence (AI), "AI will revolutionize the practice of Intelligence. […] Machines will sift troves of data amassed from all sources, locate critical information, [...], fuse data sets from different domains, identify correlations and connections, redirect assets, and inform analysts and decision-makers." [12]. The application of AI to the Intelligence Cycle will allow a permanent evaluation of the performance of MASINT systems, which will influence the use of these means throughout the cycle. Indeed, one of the great challenges in the future use of Intelligence acquisition means is the need to transform the current information management system from linear and non-integrated processes to integrated systems. It will allow to maintain a continuous system that produces predictive Intelligence, a basis for prevention and the ability to react early on the threat.

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3 Current and Promising MASINT Technologies for Detection, Identification, and Sampling of CBRNe

The acceleration of technological development processes and their impact on operational processes is a matter of extreme interest in the field of security and defense. In, this field the technologies that are arriving or are already in full development have four main characteristics: Intelligent, Digital, Distributed and Interconnected. These features will be present in the developments of scientific and technical disciplines in the coming years, in fields such as data science, Quantum Computing (QC), AI, biotechnology, autonomous systems, space technology, hypersonic speed and new materials. In particular, the combination of the developments of these disciplines will have enormous potential capable of disrupting operational processes and transforming them radically [13].

As already noted by NATO, the combined effects of technological developments and operational processes will impact several areas of operational intelligence activity, also influencing the future performance of MASINT. These include geolocation accuracy, autonomous systems, networks and expanded domains to integrate the physical and non-physical in the so-called Internet of Things (IoT) [14]. Future developments will also affect materials, such as batteries and technologies applicable to space activity for Earth observation (EO), as well as they will in some cases have an impact on the field of MASINT [14]. Advances in data science, AI, and solutions for the autonomous performance of the systems will allow us to advance in the unattended hyper-sensing of the operating environment, the automation of MASINT actions, both in acquisition and exploitation and particularly in the activities of the so-called Cross Cueing (X-CUEING) [15]. X-CUEING is "*the oriented activation by one sensor of its elicitation activity on the basis of information obtained by another sensor, generally occurring in near-real time or with little delay between the result of the 1st elicitation action and the triggering of the 2nd elicitation action*" [16]. The combination of technological developments will have clear multiplier effects, with the possibility of transforming some processes. For example, advances in data science and QC will increase the processing and analysis capabilities of MASINT data, improving the ability to face future CBRNe threats and risks [17]. Below are some of the current MASINT tools and promising technologies for CBRNe detection, identification, and sampling.

3.1 Chemical Agents

Ion Mobility Spectrometry (IMS) is the most frequently used technique in instruments for field presumptive analysis [18]. IMS is the study of how ions move in gases under the influence of an electric field, and, indeed, it can detect gaseous chemical agents. A typical IMS device comprises a chamber divided into an ionization cell and a drift cell [19], where the separation and detection of ions happen.

Flame Spectrometry studies the interaction of matter and radiated energy, such as light and other many forms of electromagnetic radiation – i.e., wavelengths, frequencies – and times – i.e., Time of Flight. Flame emission spectrometry is used for detecting alkali elements like lithium, sodium, and potassium, among others [19].

Photoionization Detector (PID) is a type of gas detector, which has a short-wavelength ultraviolet lamp for ionizing gas sample [20]. Many chemical warfare agents – i.e., nerve agents and related compounds – can be detected by PID [21].

Raman and infrared (IR) detectors are portable chemical detectors that take advantage of the physical-chemical characteristics of matter in the presence of light emitting in the IR spectrum or a laser that causes Raman-type light scattering [20]. Fourier-Transform Infrared (FTIR) spectrometers are the third generation of infrared spectrometers. The major difference between the second-generation IR devices and FTIR instruments is that IR uses a monochromatic system, whereas the FTIR uses a Michelson interferometer. IR and Raman spectroscopy are both analytical techniques used for examining the vibrational modes of molecules, but they rely on different principles and yield diverse types of data. Consequently, they are often used together to obtain a more complete understanding of a sample's composition and structure. In general, both techniques are considered non-destructive and work on most solid and liquid samples. There are also FTIR analyzers for gaseous compounds in the chemical industry, and manufacturers are gradually starting to add Chemical Warfare Agents (CWA) to their libraries with TIC. Both Raman and FTIR provide specific information (spectra or chemical CAS), and do not require sample preparation, but both technologies have strengths and weaknesses depending on the chemical compound to be identified and the medium in which it may be dissolved.

Nowadays, there are many Raman and FTIR hand-held or portable identification instruments and in case of no previous data about toxic chemicals within hot zone, the best decision for First Responders would be to use both so as they complement each other.

Standoff detection provides early warning of a chemical threat, as well as real-time visualization of a gas cloud and detection of CWAs or Toxic Industrial Chemicals (TICs). They are based on FTIR technology and are suited for both military and security operations. Each gas has its own absorption spectrum, and it shows typical absorption peaks in infrared bands, so that detector uses every gas peak to identify them. Standoff detection techniques encompass the remote sensing and identification of substances or materials without physical contact. Some common techniques include IR spectrometry, Raman spectrometry, FTIR and Light Detection and Ranging (LIDAR) [22]. These methods enable the detection of hazardous materials from a distance, ensuring personnel safety by avoiding direct exposure to potential risks.

Gas Chromatography and Mass Spectrometry (GC-MS) is a superior technique to other spectral ones in the combination of features such as sensitivity, selectivity, and generation possibility of molecular mass/formula. It has the highest potential for qualitative determination of complex organic compounds in complex mixtures. The standard instruments combining GC-MS usually include electron ionization and quadrupole mass analyzer [23]. A Mass Spectrometer can identify volatile organic compounds (VOCs) by prior separation of the different components in gas mixture in the GC, and subsequent ionization in the MS. A mass spectrometer can have a quadrupole, an ion trap, a time-of-flight analyzer, an orbitrap, or even an ion cyclotron resonance. GC-MS devices with a single quadrupole are rather simple and have been greatly reduced in size and weight, allowing its portable use at the crime scene to find chemical signatures, especially of VOCs with a mass range down to a few hundred of atomic mass units (AMU). Logically, portable GC-MSs do not meet some requirements of laboratory instruments, but they are good enough to work on hot zones and obtain signatures for attribution of cause or origin. Modern laboratory mass analyzers are already using triple quadrupole, ion trap, time-of-flight, quadrupole time-of-flight, orbitrap, and ion cyclotron resonance.

Proton Transfer Reaction and Mass Spectrometry (PTR-MS) is an ultra-sensitive technique for real-time detection of diverse volatile organic compounds (VOCs). Although the size and volume of PTR-MS instruments have been greatly reduced, they have not yet reached the point of portability, with the smallest weigh up to 80 kilograms. Apart from less time of response and lower detection limit, Time of Flight mass spectrometers, due to their high mass resolving power, can separate between isobars, hence allow for identification of compounds which have the same nominal mass [24].

Multispectral and Hyperspectral Imagery are optical spectroscopy imaging techniques. Spectral images have three dimensions, where two are spatial dimensions (x,y) and one is a spectral dimension (λ). The difference between Hyperspectral Imagery (HSI) and Multispectral Imagery (MSI) is based on the spectral dimension. HSI works with tens or hundreds of images that correspond to continuous wavebands, while MSI employs a few images (usually <10 images) that correspond to certain discrete wavebands [25]. Right now, the main challenge is to develop HSI and MSI systems that are more economic, compact, and easy to handle [25]. Nowadays, there is a satellite developed by the Italian Space Agency, which is a cutting-edge Earth Observation satellite launched in 2019. It is focused on Hyperspectral Imagery called Hyperspectral Precursor of the Application Mission (PRISMA) [26]. It can detect the chemical-physical composition of the surface of the Earth, since each material has its own spectral signature, like an actual fingerprint.

As regards promising technologies, the main ones are listed below.

(a) *Chip-type gas sensor and AI*. One of the most promising technologies is Artificial Intelligence for Chemistry. The use of AI can be applied to any analytical chemistry technology or even to other scientific fields, such as multispectral or hyperspectral optics. The key to success is to design algorithms that can identify patterns from chemical or optical identification technology. From IR spectra to pixels, algorithms can learn to recognize when a pattern corresponds to an aggressive Novichok nerve agent or a blistering liquid. Published in the journal “Lab in a Chip” in 2020, the article “AI on a Chip” [27] explains that what is essential for the development of AI is the data. Chips-type gas sensors may go by many names – Metal Oxide Semiconductor (MOS) or Complementary (CMOS) – but they are all characterized by their small size, increasingly miniaturized size, low power consumption, and the use of a semiconductor substrate with a catalytic dopant. MOS or CMOS based sensors are the most suitable for cost sensitive, low-power applications such as disposable medical, smart home, and consumer [28]. MOS sensors detect concentration of various types of gases by measuring the resistance change of the metal oxide due to adsorption of gases. The link between chips based on MOS or CMOS technology and AI is of utmost importance to improve the electronic nose concept [29], and to identify chemicals at low cost.

(b) *Hyperspectral Imaging*. NATO has been devoting increasing attention to Hyperspectral Imaging technology. Fruit of this effort is the STO-TR-SET-240 report [30] that reflects a promising future for discovering buried and hidden explosives or Improvised Explosive Device (IED) below the surface, as well as for the detection of Volatile Organic Compounds (VOCs). Night Vision and Electronic Sensors Directorate (NVESD, from US Army C5ISR Center) has developed several spectral imaging sensors in their thermal infrared. According to this work, the Longwave Advanced Compact Hyperspectral Imager (LACHI) [31] was one of the sensors used to perform measurements. Developed by Wavefront Research, LACHI is a slit scanning, cryogenic spectrometer that acquires approximately 256 spectral channels of information, with a small amount of band overlap between channels.

3.2 Biological Agents

Biological detection and alarm systems are intended to warn of the arrival of biological clouds that contrast with the previous environmental background. These are designed to trigger an alarm signal when certain concentration and time thresholds are exceeded. After the alarm, the detector can proceed to take a sample with a high flow rate sampler, which can be further analyzed to find out if the bioburden corresponds to a Biological War Agents (BWAs).

Detection Sensor based on scattering and Laser Induced Fluorescence (LIF). These systems do not provide certainty as to whether the newly arrived bio cloud contains biological agents or other biological particulates. More advanced systems include a sampler that collects an airborne sample and deposits it on a solid or liquid carrier. The most advanced biological detection and alarm systems are based on light scattering and LIF technology [32].

Identification by Deoxyribonucleic acid (DNA) is based on Polymerase Chain Reaction (PCR) by amplification of specific DNA fragments and uses each of the four bases of DNA [33]: dATP for adenine, dCTP for cytosine, dGTP for guanine, and dTTP for thymine.

Identification by immunochromatography. There are different immunological assay formats and commercial products to identify BWAs. Most common immunological test on the ground using Lateral Flow Assay (LFA) test strips [34] are known as Hand-Held Test Kits (HHTK). In laboratories, the standard immunological test is Enzyme-Linked Immunosorbent Assay (ELISA). ELISA is a labelled immunoassay that is considered the gold standard of immunoassays [35]. This immunological test is very sensitive and is used to detect and quantify substances, including antibodies, antigens, proteins, glycoproteins, and hormones.

Some promising technologies have been identified.

(a) *Bio-AeRosol Detector (BARDet) for real time air monitoring.* The BARDet instrument [36] is a new technological approach to air monitoring combining laser induced fluorescence particle characterization technique with internal computer that performs real-time data analysis and classification. In consequence, the BARDet could be used as a remote sensor integrated with a robot. This introduces a new quality and improves versatility of air monitoring.

(b) *BD21 Project.* US Department of Homeland Security (DHS) agencies, Science and Technology Directorate (S&T) and Countering Weapons of Mass Destruction Office (CWMD), have been working for years to overcome BioWatch capability gaps. In this sense, the Biological Detection for the 21st Century (BD21) Project [37] presents a paradigm shift. Its concept includes continuous monitoring for airborne releases of a biological agent using anomaly detection sensors and data analytics, and timely notification of a potential threat to authorities in addition to onsite field screening with portable equipment. BD21 will enable first responders to take immediate actions that minimise the impact of a biological release, and earlier delivery of biological samples to laboratories for confirmatory analysis that supports additional response actions and deployment of medical countermeasures.

(c) *SensNet Project.* S&T's SenseNet Project [38] is coordinated and aligned closely with BD21. Although both programs are addressing the indoor biological aerosol release, SenseNet puts the spotlight on cleaner, smaller environments like office buildings, while BD21 is evaluating more varied environments with higher concentrations of people. SenseNet uses simple particle counters and change-detection analytics to trigger an alert, followed by a presumptive identification step. S&T is currently funding the development of an automated sample collection and polymerase chain reaction capability, as well as a Matrix-Assisted Laser Desorption/Ionization Time of Flight (MALDI-TOF) mass spectrometer for SenseNet presumptive identification purposes.

(d) *C-Clean Project. Hyperspectral imaging for identifying viruses*. The Spanish C-CLEAN project was developed within the framework of the COVID-19 Emergency Call from the Carlos III Health Institute. The project title was *Proof of concept of rapid detection of SARS-CoV-2 contaminated surfaces by multispectral optical and holographic analysis with Artificial Intelligence* and was developed at the University of Seville with the support of the EOD-CBRN Group of the Spanish National Police. The goal was to find viruses on surfaces by analyzing hyperspectral images taken at multiple wavelengths. The project team employed images taken at multiple wavelengths in the visible and near-infrared ranges and processed them through advanced statistics algorithms and AI. The technique registers images of the samples arranged in a matrix and determines the positions in which the virus is detected, as well as its concentration. So far, researchers have published two open reports about the project. The first one was about an experiment to ascertain if Hyperspectral Imaging could detect so small particles as viruses [39]. The second experiment was specifically designed to identify SARS-CoV-2 virus with hyperspectral image analysis in the visible and near-infrared range [40].

3.3 Radiological and Nuclear Agents

Just as in the case of chemical and biological substances, concerning threats posed by nuclear and radiological substances, it is necessary to differentiate between detection and identification. Detection involves manifestations through gamma rays, high or low energy, or alpha and beta particles. Detection devices fall into categories such as Electronic Personal Dosimeters, Personal Radiation Detectors, and Radiation Survey Meters. Conversely, identification involves discerning the specific radioisotope or radioisotopes present, enabling appropriate measures for affected personnel and the remediation of affected areas. Spectral Personal Radiation Detectors and Radioisotope Identifiers facilitate obtaining spectral signatures and isotopic names [41].

Detection devices provide measurements in dose rate (Sv/h), dose (Sv), or surface contamination (Bq/cm^2). Identification instruments yield signatures based on radiation energy peaks (keV) that are compared with a device radionuclide library. Clear energy peaks allow detectors to identify radionuclides, while unclear readings may necessitate laboratory analysis or reach-back capabilities to determine potential shielding or a mixture of radioisotopes [42].

Nuclear radiation, defined as ionizing radiation, can be detected using various technologies. Three main types of radiation detectors exist, each with strengths and weaknesses suited to specific roles [43]: (1) *Gas-filled detectors*: Ion chamber detectors measure absorbed dose over time, suitable for high-energy gamma rays. Proportional counters differentiate energies, valuable for spectroscopy applications. Geiger Muller (GM) tubes are common for detecting radioactive contamination, primarily functioning as counting devices. (2) *Scintillators*: Scintillation detectors are highly sensitive, producing flashes of light for each photon interaction. They capture spectroscopic profiles, making them useful for radiation security applications. Common inorganic scintillators are made of sodium iodide (NaI) with thallium impurities [44]. (3) *Solid-*

state detectors: using semiconductor materials like silicon or germanium, these detectors operate similarly to ion chambers, but at a smaller scale and lower voltage. They have a short response time and can withstand higher radiation levels over their lifetime [45].

Additionally, the US Nuclear Detonation (NUDET) Detection System (NDS), installed on some Global Positioning System (GPS) satellites, monitors nuclear detonations worldwide [46]. The NDS packages include X-ray and optical sensors, Bhang meters, Electronic Magnetic Pulse (EMP) sensors, and data-processing capabilities for accurate location detection [46]. The US Defense Meteorological Satellite Program (DMSP) spacecraft has hosted various AFTAC sensors, including the SSB Gamma Tracker, SSB Gamma X-Ray Detector, and SSB/A X-Ray Spectrometer for tracking fallout, detecting X-rays and gamma rays, and monitoring electromagnetic radiation [47].

In terms of promising technologies, in addition to the detection and identification of nuclear radiation, various components of MASINT contribute to obtaining measurements and signatures of radioactive sources. Despite radioactivity being referred to as the “shadow enemy”, responses can be elicited in certain wavelengths, particularly within the ultraviolet light spectrum. The European project RemoteALPHA [48] aims to develop innovative optical systems for remotely detecting and quantifying large-scale contamination with alpha emitters in outdoor environments. This project enables prompt and effective countermeasures in the event of a radiological emergency. Notably, it employs outdoor radioluminescence for alpha emitter detection at the distances exceeding two meters, utilizing ultraviolet (UV) illumination lamps mounted on drones. Primary alpha emitters of concern include Pu-239 (Category I of Special Nuclear Material per the US Atomic Energy Act of 1954), Pu-238, U-238, Th-232, Am-241, and Ra-226.

Furthermore, the potential of satellite services plays a crucial role in obtaining information related to nuclear and radiological threats, even when sourced from open platforms in the visible spectrum. Initiatives such as Copernicus Security Service, Copernicus Data and Information Access Services (DIAS), and Copernicus Emergency Service, as well as various data providers and mapping companies, provide imagery and value-added services in visible wavelengths and hyperspectral ranges. The James Martin Center for Non-Proliferation Studies (CNS) at the Middlebury Institute of International Studies in Monterey leads the Geo4nonpro initiative [49], a group of experts voluntarily dedicated to in-depth analysis of open-source imagery to enhance understanding of well-known sites in relation to proliferation activities. Geo4nonpro offers satellite images, either free from Google Earth or through paid imagery from private systems, for joint surveys of specific locations in China, Iran, North Korea, Russia, and Vietnam [50]. In 2018, the CNS released an occasional paper titled “Monitoring Uranium Mining and Milling in China and North Korea through Remote Sensing Imagery” [51]. Based on open sources, this paper discussed the then-existing lack of hyperspectral open sources to enhance information about uranium production.

3.4 Explosive Agents

Explosives are chemicals just like CWAs, and, therefore, they can be analyzed by basically all techniques applicable to chemical agents (if there is sufficient volatility). The most crucial capability for detecting and identifying explosives from a safe distance is the ability to foresee explosive threats without entering hazardous areas. This capability is also employed by Intelligence for early detection of explosives use and preparation [52]. The NATO Scientific & Technology Organization has formed a Task Group (TG) within Panel SET-316 [53], titled “Realistic Trace Explosives Test Standards for Evaluation of Optical Sensors in Relevant Scenarios”. The purpose of this TG is to establish standardized methods for creating chemically contaminated surfaces using printing techniques. These surfaces will simulate realistic hazard levels to evaluate the effectiveness of explosives standoff/point detection systems. These systems could be employed in various scenarios such as checkpoints, temporary roadblocks, and sensitive site exploitation. The TG aims to develop standardized deposition techniques for generating samples to assess a variety of explosives detection sensor technologies.

As for promising technologies, numerous scientific publications delve into the realm of remote explosives detection, with a considerable focus on Hyperspectral Imaging. The initial studies concentrated on blue light and UV spectra, exemplified by *Detection of Explosives by Differential Hyperspectral Imaging* [54].This approach focuses on identifying explosive materials on various surfaces such as luggage, parcels, shoes, and garments from a distance. The technique involves shining UV and blue light on a surface, like a piece of luggage on a moving conveyor belt. Subsequently, the reflected light is collected, diffracted by a spectrometer, and its intensity is recorded with a Charge Coupled Device (CCD) camera. The resulting data undergoes computer processing, generating a differential reflection spectrum. Renowned for its high sensitivity, this differential technique provides detailed spectroscopic data, particularly on explosives. This study successfully demonstrated the accurate identification of various explosive substances, including 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), Composition C-4 (C-4), Pentaerythritol tetranitrate (PETN), and ammonium nitrate (AN), down to the low microgram range through differential reflection spectroscopy. This standoff technique is characterized by its speed, eye safety (no laser light or X-ray), automation, and independence from human involvement.

In subsequent years, another research team explored Hyperspectral Imaging using an IR lamp instead of UV [55]. The objective was to determine optimal wavelengths for detecting three types of explosives: AN, C-4, and TNT. The study identified 22 wavelengths out of 144 as the most effective. Despite the limitations of laboratory conditions and an artificial light source for trace detection, models developed using these optimal wavelengths achieved acceptable results, with an accuracy of 77.17 %. In comparison, the model using spectral values from the entire 400-1 000 nm spectrum achieved an accuracy of 81.11 % [55]. Nowadays, the EOD-CBRN group of the Spanish National Police in Seville, in collaboration with the University of Seville, is researching mobile Hyperspectral Imaging solutions like the Specim IQ camera for field-based explosives identification [56]. Their approach involves comprehensive testing, encompassing equipment preparation, calibration, light control, precise imaging distance measurement, sample scanning, and laboratory data processing through comparisons with existing databases. Their future objectives include further exploration of unmanned ground vehicle (UGV) robots for photography and the integration of AI/Machine Learning (ML) [56].

4 Remarks and Recommendations

The above-described advances in MASINT and other technology innovations in the detection, collection, and analysis of CBRNe samples will drive the fight against

CBRNe threats. In the following, some thoughts and recommendations are discussed about the whole CBRNe intelligence cycle, both within and outside MASINT activities, and about the need of adopting a holistic approach to rise efficiency.

MASINT data analysis and alert Intelligence software. Dealing with large volumes of data requires innovative architectures and techniques to extract relevant knowledge. This involves harnessing technologies such as AI, ML, QC, and Big Data (BD) technology. Alert Intelligence plays a crucial role in automating and systematizing the identification of MASINT signals, facilitating a more effective response to CBRNe threats.

MASINT, sensors, robotics, and autonomous systems. The ongoing miniaturization and enhancements in batteries, along with strides in energy autonomy through self-generation or "near-zero power" solutions, are poised to result in significantly expanded capacities for sensor deployment across extensive operational environments [57]. Progress in autonomous systems, batteries, and the connectivity of unattended sensors is expected to facilitate the expansion of the MASINT sensor network, amplify the collection of signals and signatures, and thus enhance capabilities for systematic and continuous monitoring, analysis, and identification. This is particularly crucial in high-risk areas and situations, where improved sensor networks can contribute significantly to heightened situational awareness and response capabilities.

Space-based persistence MASINT surveillance. It holds significant promise, particularly in the MASINT CBRNe domain. This revolutionary shift is anticipated to be driven either by commercial providers or by the development of in-house capabilities in the coming years, initiated by national or multinational security agencies. These capabilities will be enhanced through improved sensor power on geostationary satellites or, in the short term, through the deployment of mini-satellite constellations. Advances in size, weight, power, and costs (SWaP-C) will not only bolster the potency of these capabilities but also render them more economically feasible.

Predictive Intelligence and decision support. In the domain of predictive Intelligence, MASINT CBRNe stands out for its applicability in utilizing BD and mathematical models to estimate the consequences and effects of actions. It is essential that these computational applications and the functional systems supporting them are seamlessly integrated into police command and control or emergency management systems for CBRNe. Furthermore, these systems should offer operational personnel a comprehensive Common Operational Picture (COP) by directly incorporating information on future CBRNe threats and their potential consequences onto situation maps. This integration significantly enhances overall situational awareness and preparedness for responding to CBRNe incidents.

Towards a comprehensive approach to the CBRNe threats. In the context of a multi-domain approach, CBRNe defense, or CWMD, extends far beyond the confines of the CBRNe sphere. Just as the comprehensive approach taken by military Intelligence in countering the threat of Improvised Explosive Devices, this effort requires a broadened focus that coordinates with various disciplines. It involves examining aspects that may seem distant from the immediate CBRNe action but are essential precursors, including radicalization, recruitment, financing, transportation, precursor manufacture and acquisition, command and control structures, and network propaganda. While it may seem that these considerations go beyond the scope of this article, it is important to emphasize that the greatest risk in Intelligence concerning threats lies in adopting biased and stovepipe-based approaches to different disciplines and research areas. Despite its significant technical dimension, especially in the procurement phase, MASINT is fundamentally rooted in the social sciences. Therefore, it can and should draw upon insights from these disciplines to enhance the efficiency of its processes. A holistic understanding that integrates technical and social dimensions is crucial for a comprehensive threat assessment and response.

Biotechnology and human-machine integration. This field represents a frontier with promising developments. In the medium to long term, these advancements are poised to transform the human body into a sensor, particularly applicable in the realm of MASINT CBRNe. This transformation will extend to both the detection of CBRNe agents and the biomedical monitoring of their impact on human beings. The emerging ability to utilize techno-sensing animals holds significant potential, offering enhanced capabilities in detecting and evaluating the effects of unknown CBRNe threats.

5 Conclusion

MASINT plays a crucial role in providing unique insights and intelligence in various real-world applications. Indeed, it offers distinctive capabilities for gathering and analyzing intelligence across different domains, including national security, disaster response, environmental protection, space situational awareness, and nuclear proliferation monitoring.

Considering the high potential and capabilities of existing technologies, the future presents significant challenges in addressing CBRNe risks and threats. Traditional CBRNe methods remain a concern, as entities with limited resources can employ them to cause devastating impacts. Effective CBRNe defense hinges on anticipation, facilitated by technologies enabling the continuous deployment of specialized networks of compact and automated MASINT sensors. These networks would allow constant and efficient monitoring of CBRNe threats. Miniaturization and automation play a crucial role for achieving widespread dispersion and coverage, creating CBRNe-protected areas.

As technology continues to advance and new MASINT techniques emerge, its real-world applications are expected to improve and evolve, albeit with ongoing challenges in implementation and adaptation.

Future MASINT sensor networks should be interconnected through a Machine-to-Machine (M2M) network for immediate and efficient CBRNe threat identification. This requires computerized systems with QC and BD capabilities, equipped with extensive databases of signatures and signals for swift threat identification. Developing this capability transcends the capacity of an individual European State, necessitating a global effort by States and supranational organizations to provide common and effective tools against CBRNe threats. A major challenge lies in the absence of common standards for exchanging information on new signatures and signals of CBRNe means, hindering the creation of common MASINT databases. Furthermore, achieving a common approach among EU Countries regarding CBRN/CBRNe threat information and data exchange is imperative. Finally, the authors underscore the importance of adopting a holistic approach within the Intelligence Cycle to enhance overall efficiency in fighting CBRNe threats.

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