JCBRN Defence COE
per virtutem ad securitatem

ROLE OF UNCREWED VEHICLES IN CBRN DEFENCE

JCBRN DEFENCE COE WORKING PAPER

Lucie SEDLÁČKOVÁ with a team of authors

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By Lucie SEDLÁČKOVÁ

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Contents

1. Preface

By Lucie SEDLÁČKOVÁ

In contemporary times, encountering someone who has yet to hear of uncrewed vehicles (UxV) is rare. Although the inception of UxV traces back to the early 20th century, their widespread adoption has surged only in recent years. This growth owes much to technological advancements, including robust processors, sophisticated sensors, and precise global positioning systems. As a result, UxV have become capable, reliable, and forceful tools. Moreover, they have become more accessible and customisable, catering to a broader audience.

Recognising UxV potential, militaries have swiftly integrated them into their arsenals, primarily for intelligence, surveillance, and reconnaissance (ISR) operations. Still, there is increasing employment in the form of loitering munitions, and UxV can be employed in both a defensive and offensive role. The recent conflict in Ukraine shows, that the employment of UxV from ordinary civilian production has excellent potential for various military purposes.

These developments underscore the necessity of fully leveraging the capabilities offered by UxV to conduct operations in the CBRN environment and be prepared to defend against UxV being used as a delivery system for CBRN materials. Maintaining a safe distance from such CBRN hazards is paramount, making UxV indispensable in aerial, terrestrial, and maritime settings to increase early warning of potential attacks and reduce personnel exposure to such CBRN threats. CBRN defence units can exponentially enhance their effectiveness and efficiency by harnessing UxV technology alongside artificial intelligence (AI) and robotics.

This working paper aims to develop and share insights into current UxV utilisation and provide a foresight of UxV's future role from the point of CBRN defence.

The working paper consists of 8 chapters. Chapter 3 brings you into the discussion about the status of using UxV for CBRN defence via analysis of NATO Capstone Capabilities influenced by UxV and their current use level for CBRN defence tasks. Chapter 4 provides an overview of the research and development of UxV in CBRN defence and practical examples for accomplishing CBRN defence tasks. Chapter 5 analyses UxV implications on the NATO CBRN defence enabling components, and Chapter 6 explores limitations and gaps related to CBRN defence enabling components and military operational usage. Finally, Chapter 7 will familiarise you with future trends in the involvement of UxV in executing CBRN defence tasks. In contrast, Chapter 8 assesses their status and future development's usage in CBRN defence. Moreover, the Annex presents industry data sheets of UxV involved in CBRN defence.

Based on the NATO Gender-Inclusive Language Manual[1], the term uncrewed vehicles (UxV) is used throughout this working paper instead of unmanned vehicles. Unfortunately, NATO hasn´t established an agreed term for uncrewed vehicles[*], but there is an approach to use this term within NATO nations. For the reader to be familiar with the notion of uncrewed vehicles, we propose that UxV can be defined as self-propelled vehicles that operate without onboard human intervention in land, maritime, air, or even in a combination of these environments, like amphibious vehicles. Still, based on the existing identical terms regarding unmanned and uncrewed vehicles, it is expected that *unmanned* will be replaced by *uncrewed*.

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[*] Note: According to NATO Terminology, the following term exist: unmanned ground vehicle (UGV): A self-propelled ground vehicle that operates without on-board human intervention.

2. Introduction

By Lucie SEDLÁČKOVÁ

UxV stand as a cornerstone in the evolution of modern military defence strategies, offering a large variety of platforms ranging from UxV and robots to autonomous vehicles. Within the CBRN environment, these platforms can be employed in both a defensive and offensive role. Hence, adversarial employment of these platforms to deliver CBRN substances changes the threat paradigm for CBRN defence considerations. Therefore, this working paper focuses on employing these platforms to enhance CBRN defence capabilities. UxV have the versatility, agility, and capacity to navigate through hazardous environments, making them indispensable assets in CBRN defence. Emphasising their pivotal role, the NATO Science & Technology Organization (NATO-STO) underscores the significance of UxV in military operations, highlighting their critical contributions to ISR missions.

Furthermore, using small UxV swarms presents considerable advantages for ISR during offensive and defensive operations, showcasing the dynamic landscape of modern warfare. These swarms offer enhanced capabilities such as distributed sensing and increased survivability through redundancy. Moreover, advancements in AI and autonomous systems have augmented their effectiveness, allowing for decentralised decision-making and adaptive responses to dynamic environments.

Looking ahead, the direction and speed of technological trends indicate a profound impact on military defence, particularly in the CBRN defence domain. Forecasts anticipate a transformative shift wherein UxV and autonomous software agents assume operational roles traditionally performed by humans, mainly in hazardous environments. This transition underscores the imperative for the military to adapt in terms of technological integration, cultivating requisite skills, reconfiguring organisational structures, and refining training methodologies.

As autonomous systems are increasingly incorporated into military operations, proactive measures will be essential to ensure readiness and effectiveness in the face of evolving threats and challenges. Strategic investments in research and development, collaborative partnerships with industry leaders, and ongoing education and training initiatives will be crucial to harnessing UxV's full potential in safeguarding national security interests. By embracing innovation and UxV's transformative capabilities, military organisations can navigate the complexities of modern warfare with agility, resilience, and strategic foresight.

3. Uncrewed Vehicles in CBRN Defence

3.1 Analysis of NATO Capstone Capabilities Influenced by Uncrewed Vehicles

By MAJ Bruno FERRANDES

"Bi-SC Capability Codes and Capability Statements" (CC&CS) provide a common language for capabilities in defence planning and operations planning. The CC&CS describe capabilities at a sufficient level of granularity for requesting forces, noting that necessary mission tailoring could result in deviations from an original capability statement.[2] They are widely used throughout NATO and have also been adopted by the European Union Military Staff for use in both their long-term and operations planning. The following paragraphs analyse the CBRN capability statements that UxV mainly influence.

3.1.1 CBRN Reconnaissance

Aerial surveillance is one key aspect where uncrewed aerial vehicles (UAV) equipped with advanced sensors like light detection and ranging, infrared cameras, and gas detectors can swiftly detect, and map areas contaminated with CBRN substances. By flying at varying altitudes, they cover large areas efficiently.

Remote sensing technologies carried out by UAV, such as hyperspectral and multispectral imaging, will play a vital role in detecting and identifying CBRN threats. These sensors detect specific wavelengths of light emitted or reflected by CBRN substances, aiding in their identification and characterisation.
UxV equipped with air sampling devices can collect samples from suspected areas of CBRN contamination. Analysis of these samples may confirm the presence of CBRN substances, enabling commanders to guide their response efforts. Chemical and biological sensors onboard UxV provide real-time data on the presence and concentration of hazardous substances, facilitating rapid response and mitigation efforts. Radiation detection capabilities in UxV enable the identification and mapping of radiation hotspots in areas affected by nuclear or radiological incidents, helping assess contamination levels.

Integrating AI and machine learning allows UxV to analyse reconnaissance data, identifying patterns and anomalies associated with CBRN threats, thus enhancing detection capabilities. Real-time monitoring provided by UAV transmits data and imagery to command centres or response teams, facilitating quick decision-making and resource deployment to mitigate the impact of CBRN incidents. Autonomous operation, enabled by advancements in technology, reduces the need for constant human intervention, allowing prolonged reconnaissance missions and enhancing the efficiency of CBRN detection and monitoring tasks.

3.1.2 Aerial Radiological Survey

The key advantage of radiological remote sensing relays on using UAV equipped with specialised sensors such as gamma-ray detectors or spectrometers. These sensors accurately identify and quantify radiation sources from a safe distance, offering invaluable insights into radiation distribution.

Efficient coverage is another crucial aspect where UAV excel. They can swiftly cover large areas, providing comprehensive radiation data over a wide geographic area in a relatively short time. This capability proves particularly beneficial in emergency response situations or when conducting surveys in remote or inaccessible locations, where timely and accurate data is critical.
Furthermore, integrating high-resolution imaging capabilities in some UAV allows for the capture of detailed images of the surveyed area. Combining radiation data with high-resolution imagery enhances analysis and interpretation, providing a deeper understanding of radiation sources and their surroundings.

Advanced UAV's real-time monitoring capabilities enable operators to receive real-time data, allowing for the immediate identification of hotspots and swift decision-making during the survey process. This real-time feedback ensures that survey parameters can be adjusted as needed, optimising efficiency and effectiveness.

Significantly, UAV enhance safety by minimising the risk of surveyors' exposure to radiation. By keeping human operators at a safe distance from potential radiation sources, UAV ensure the safety of personnel involved in surveying activities.

UAV afford unparalleled flexibility and accessibility, as they can access areas that may be difficult or dangerous for ground-based survey teams to reach. Whether navigating rugged terrain, contaminated sites, or areas with limited infrastructure, UAV enable comprehensive survey coverage, providing a better understanding of radiation distribution in various environments.

Integration with Geographic Information Systems (GIS) further enhances the effectiveness of aerial radiological surveys by facilitating analysis, visualisation, and mapping of radiation contamination levels. This spatial analysis aids decision-making for remediation efforts or regulatory compliance, optimising environmental protection measures.

3.1.3 Biological Monitoring and Detection

Properly equipped UxV are pivotal in collecting air samples from potentially contaminated environments. These samples can then undergo onboard analysis or be transported to laboratories for thorough examination, facilitating the detection of biological warfare agents. This capability minimizes human exposure to hazardous substances while efficiently gathering crucial data. Moreover, integrating biological sensors into UxV enables real-time detection of specific biological warfare agents in various mediums such as air, water, or soil. This capability empowers rapid response and mitigation efforts by providing immediate insights into the presence and concentration of biological warfare agents.

Remote sensing technologies enhance detection capabilities by equipping UxV with hyperspectral and multispectral imaging capabilities. These advanced sensors can identify anomalies associated with biological contamination, such as changes in vegetation or environmental factors, aiding in the early identification of potential threats.

Using AI and machine learning algorithms further augments the effectiveness of UxV in biological detection. By analyzing data collected during reconnaissance missions, these algorithms can identify patterns and anomalies indicative of biological threats, enhancing overall detection capabilities.

Real-time monitoring capabilities of UxV enable swift decision-making and resource deployment in response to biological incidents. By transmitting data and imagery to command centres or response teams, these platforms facilitate efficient and coordinated responses to mitigate the impact of biological threats.

Advancements in navigation technology allow UxV to operate autonomously, reducing the need for constant human intervention. This allows for prolonged reconnaissance missions and enhances the efficiency and effectiveness of biological detection and monitoring tasks.

Furthermore, specialised UxV's sensors can detect bioaerosols and airborne particles containing biological warfare agents. This capability enables the identification and tracking of the movement of biological threats, facilitating containment and response efforts.

3.1.4 Decontamination

UxV with high-resolution cameras and sensors enable to perform aerial surveys of contaminated areas, assessing contamination extent and identifying hotspots, thus providing crucial data for operations planning and targeted decontamination. Moreover, UxV excel in the precise delivery of decontamination agents such as water, surfactants, chemical decontaminants or disinfectants. Their ability to navigate specific locations or inaccessible terrain increases coverage while minimizing human exposure to hazardous materials. Remote decontamination tasks represent another significant application of UxV, as they can perform decontamination tasks in hazardous environments from a safe distance. Mitigating decontamination tasks through remote capabilities extends the range and area of coverage of decontamination tasks. It also reduces the footprint of decontamination tasks, making them less susceptible to becoming targets. Remote technologies also allow for decontamination tasks to be more responsive and reduce the extent of contamination by conducting decontamination closer to the site of contamination. A key element to successful decontamination is reducing the time personnel, vehicles, and materials are contaminated. Remote and autonomous solutions can also reduce the personnel requirements for decontamination tasks.

Regarding monitoring and supervision, UxV provide real-time aerial surveillance of decontamination tasks, capturing imagery and video to assess effectiveness and identify areas needing further treatment. Additionally, UxV equipped with radiation detection and decontamination technology are crucial for mitigating radiological contamination, as they can detect and remove radioactive materials, significantly reducing radiation exposure risks.

Post-decontamination assessment and validation facilitated by UxV equipped with sensors and imaging technology enable the detection of any remaining contamination or hotspots necessitating further treatment. This validation process ensures the success of decontamination efforts and enhances overall confidence in the recovery process.

Lastly, advancements in autonomous decontamination systems enable UxV to operate autonomously, optimising resource utilisation and minimising emergency response time. These systems represent a significant leap forward in efficiency and effectiveness in CBRN decontamination tasks.

3.2 Analysis of the Current Use of Uncrewed Vehicles for CBRN Defence Tasks

By Lucie SEDLÁČKOVÁ

By sending UxV ahead to assess a potentially hazardous situation, commanders can reduce the number of people they must put in harm's way. Generally, basic capability requirements which are met include the ability to operate and perform long-term measurements in a contaminated area, collect samples, monitor spatial intensity variations of contamination, and communicate findings in real-time over an encrypted data link[3].

The prevailing opinion among NATO nations and partners indicates a shared intention to employ or advance UxV to address CBRN defence tasks. Therefore, there was a survey in May 2024 conducted among NATO nations to assess the status of UxV utilisation. The survey was primarily focused on categorising types of UxV deployed, their specific applications in CBRN defence tasks, and the status of UxV in fulfilling these tasks. Additionally, participating nations were encouraged to outline their plans and developmental engagements concerning the integration and utilisation of UxV in various operational contexts.

Based on the survey outcome, diagram 1 shows that more than 60% of responding nations do not utilise UxV to fulfil CBRN defence tasks. However, these nations grasp this issue seriously as they are involved in many research and development projects, such as European Defence Agency (EDA)/European Union (EU) projects or NATO STO projects, to enhance their CBRN defence structures with UxV.

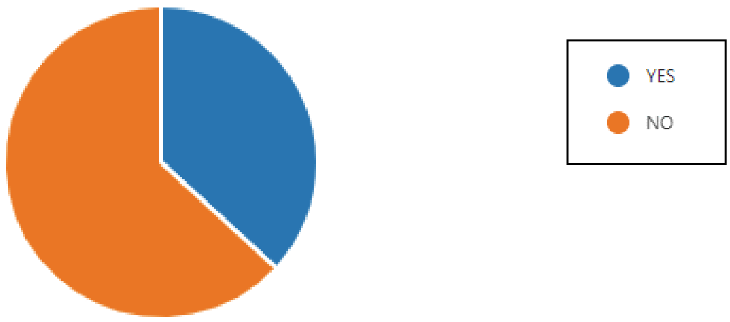

***Diagram 1:** Countries using UxV for CBRN defence tasks (based on the JCBRN Defence COE survey, May 2024)*

One of the EDA/EU projects is the CBRN Surveillance as a Service (CBRN SaaS) project initially launched as a Permanent Structured Cooperation (PESCO) project and aimed to establish a persistent and distributed manned-uncrewed sensor network consisting of uncrewed aerial system and uncrewed ground system (UGS)[4]. Later, this Austrian-led project was handed over to EDA for practical implementation to develop a rapidly deployable 24/7 CBRN surveillance capability. In 2021, the CBRN SaaS project entered the operational phase. The main expected output of the EDA Cat B project is an operational plugin module with various sensors built on uncrewed ground and aerial systems. Delivered real-time CBRN surveillance, detection and incident data will create a recognised CBRN picture for civilian and military purposes[5]. The 4th field test of CBRN SaaS was completed in April 2024 and was focused on testing a technical demonstrator in an Austrian military exercise area. That technical demonstrator is expected to be used in case of a major disaster involving the release of CBRN substance, a high-visibility event with potential CBRN threats, and during a multinational military operation. The demonstrator's advantages are mainly capabilities to predict situations after CBRN substances are released and to recalculate hazardous areas after CBRN reconnaissance. This project is unique thanks to integrating various sensors into multiple platforms operated in various battlefield management systems and setting standards for the military and industry. Besides Austria, other nations, such as Slovenia, Croatia and Hungary, are also involved in the CBRN SaaS project. Some UxV industry data sheets within this project are covered in the annex.

Focusing on nations using UxV for their CBRN Defence tasks, the survey has underscored the widespread preference for UAV and uncrewed ground vehicles (UGV), primarily leveraged for CBRN reconnaissance, detection, sampling, and identification missions. These uncrewed systems are predominantly utilised in tasks involving chemical warfare agents or radioactive materials, reflecting a concerted effort to bolster capabilities in mitigating and responding to CBRN incidents. These outcomes are depicted in diagrams 2 and 3.

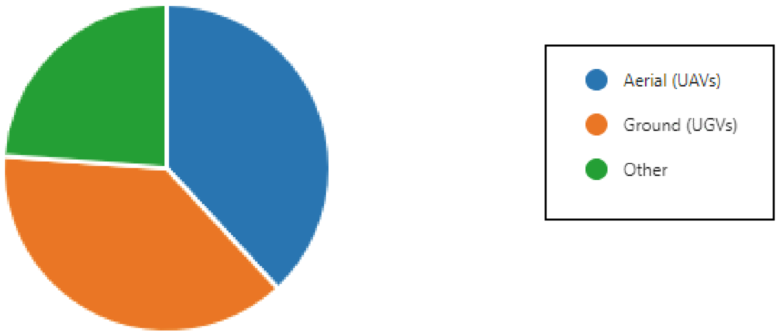

***Diagram 2:** The most frequented kind of UxV used for CBRN defence tasks (based on the JCBRN Defence COE survey, May 2024)*

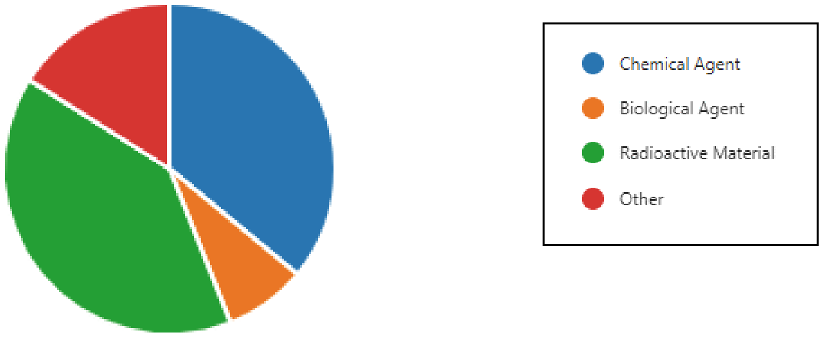

Diagram 3: *The most frequented kind of CBRN substances involved in CBRN defence tasks using UxV (based on the JCBRN Defence COE survey, May 2024)*

This collective emphasis on UxV underscores a recognition of their efficacy in enhancing situational awareness, minimising human exposure to hazardous environments, and facilitating prompt and precise responses to CBRN threats. Additionally, the survey revealed that nations already use UxV to enhance and modernise CBRN defence capabilities, such as the US Army modernising future efforts focusing on remote CBRN sensors, autonomous decontamination, next-generation CBRN reconnaissance & surveillance (CBRN R&S), and integrated communications (CBRN Command Decision Support Tools). This working paper describes in detail only the first three efforts, which are directly linked with UxV's role in CBRN defence.

Remote CBRN sensing aims to increase the area of coverage of the CBRN sensor on the battlefield while also providing standoff detection and removing the soldier from the hazard. CBRN remote sensors are expected to provide early warning by integrating them into current army and joint networks and command and control (C2) systems. Another sensor's envisioned capability is the ability to be deployed throughout the operational area to provide remote, continuous detection and identification of CBRN threats. The sensors can also be mounted on uncrewed vehicles and automated to increase the success of operations.

Figure 1: *CBRN sensor mounted on UAV*[6]

The overall concept of automated decontamination proposes an autonomy-enabled employment process to include data handoff & pre-wash, contamination mapping, automated contamination mitigation, and clearance & status tagging steps. This capability aims to unencumber the warfighter by deploying robotics, automation, and AI while pushing mitigation responses as far as the forward line of troops. The capability is expected to be automated or minimally manned, reducing time, logistics and personnel. It also utilises uncrewed ground or aerial systems to pre-check equipment for contamination and then focus on contaminated areas to minimise contamination levels to allow a return to combat operations.

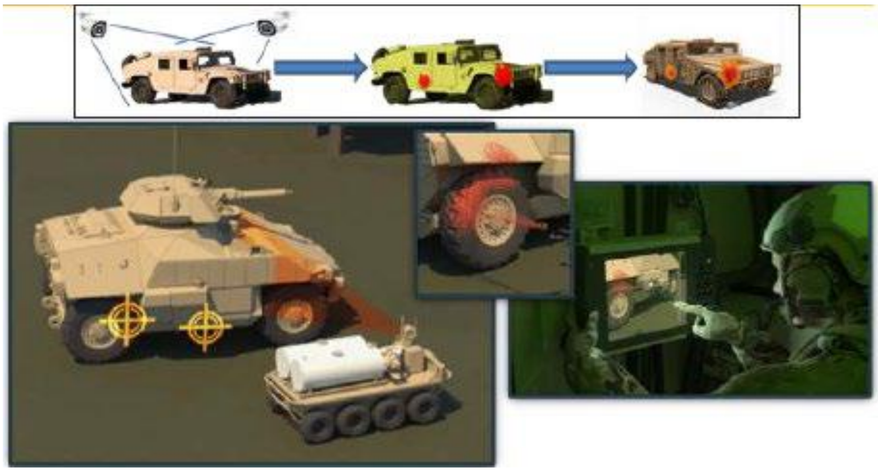

Figure 2: *Automated Decontamination architecture*[6]

The next-generation CBRN R&S goal is to remove military members from the hazard using a common sensing platform, fully autonomous reconnaissance assets, and sensors that can detect contamination in real-time. Envisioned capabilities of the CBRN R&S are distributing sensors across the field, mounting sensors on all vehicles, dropping them by soldiers or UAV and delivering by swarm to reduce cross-contamination. Fully autonomous CBRN R&S systems are expected to be paired with machine learning and AI capabilities to provide commanders with decision support tools[6].

4. Research and Development of Uncrewed Vehicles in CBRN Defence

By MAJ Miroslav LABAŠKA

UxV or robotic technology is a pivotal asset in bolstering the effectiveness of response to CBRN incidents across various domains. By furnishing precise, real-time data before and during ingress into hazardous zones, these UxV significantly influence the course of CBRN defence. However, access to such hazardous zones is contingent upon defining the hazard area, conducting preliminary hazard identification, donning personal protective equipment (PPE), and establishing decontamination facilities. Swift deployment of UxV supplements response efforts and aids in directing the overall response strategy.

4.1 Cognitive Task Analysis of Using Uncrewed Vehicles

Experts from the CBRN incident response environment have used a cognitive task analysis (CTA) to reveal the intricate cognitive processes and decisions in connection with using UxV and robots in CBRN Defence. Using goal-directed task analysis (GDTA)[7] and modified cognitive work analysis (mCWA)[8], Humprey and Adams[9] studied tasks and interactions between responders to identify UxV requirements. Their CTA integrated data from government, academia, and interviews with subject matter experts but excluded urban search and rescue (USAR) from the analysis as it was outside of the study's scope. The findings highlighted emergency evaluation, emergency management, incident/hazard mitigation, and victim care as critical areas for robot integration. The human-robot interaction (HRI) user levels have been identified to understand how UxV would impact response workflows and responsibilities. Overall, the CTA study revealed the need for a paradigm shift towards integrating UxV into CBRN response, outlining specific information UxV must gather and potential changes in human roles.

The CTA has discerned the need to compartmentalise the scene assessment task into three distinct functions, following an initial identification of five supplementary tasks. Before delving into the specifics of these tasks, it becomes imperative to outline the overarching purpose of the scene assessment task: determining the critical question of "What needs to be done in this situation?" Initially conceptualised as a singular, all-encompassing endeavour, the scene assessment task encompasses a multifaceted array of responsibilities, including hazard detection and location, identification of specific hazards, assessment of victim numbers and status, surveying the scene, and ongoing monitoring. To streamline these responsibilities, the incident functional analysis (IFA) has further dissected them into eight discrete functions, each characterised by unique constraints and attributes such as deployment speed, task execution pace, field deployment duration, sensor payload weight restrictions, and task frequency. Based on the analysis, these eight functions are covered in tasks such as survey task, identification task, scene observation/object tracking task, medical initial assessment task, medical victim transportation task, decontamination task, hazard disposal task and resource hauling task. The working paper is focused on details of the following tasks:

1. Survey Task:

The Survey task is the initial foray into the hazardous environment and encompasses six critical IFA functions. These include the collection of hazard information, epidemiological information, aerial reconnaissance, survey operations, general victim search, and technical victim search. For seamless integration into the operational workflow, UxV assigned to this task must exhibit rapid deployability, with a particular emphasis on swiftly executing functions such as aerial reconnaissance, survey operations, and general victim search to furnish vital overview information at the onset of the incident. As such, lightweight sensors are preferred to facilitate expedited task execution, aiming to provide essential hazard and victim data. UxV entrusted with the survey task yielded many advantages, including the ability to relay critical information to responders even before completing safety protocols such as PPE donning. These UxV act as force multipliers, augmenting human responders' capabilities while offering a more comprehensive dataset by integrating diverse onboard sensors.

2. Identification Task:

In contrast, the Identification task focuses more on scrutinising individual hazards within the hazardous environment. Central to this task is the function of hazard identification, necessitating a medium payload and an intermediate task execution duration. While sharing some commonalities with the survey task, particularly collecting hazard and epidemiological information, the Identification task distinguishes itself by providing a detailed analysis of identified hazards. Multiple UxV may collaborate to divide the workload to expedite this process, thereby accelerating the analysis and reporting phases. Moreover, UxV assigned to the Identification task must possess robust decontamination capabilities to endure repeated exposure to hazardous materials without compromising functionality. Additionally, integrating cost-effective, modular hazard identification systems is imperative to accommodate the diverse array of hazards encountered in CBRN incidents. This requirement underscores the need for versatility and adaptability in robotic systems deployed for identification purposes. The delineation between the survey and identification tasks underscores the nuanced nature of CBRN response operations. While the survey task provides a broad overview of hazards and victim conditions, the identification task delves deeper into hazard analysis to facilitate informed decision-making by specialised response teams. These tasks synergise to furnish comprehensive situational awareness, empowering responders at various operational levels to mitigate the impacts of CBRN incidents effectively.

3. Scene Observation/Object Tracking Task:

The scene observation/object tracking task is a critical component in the CBRN response toolkit, focusing on persistent surveillance and monitoring of incident scenes. At its core lies the coordinate field operations function, distinguished by its requirement for prolonged deployments and continuous task execution. This task encompasses functions such as aerial reconnaissance and survey operations, aiming to provide real-time, direct observation capabilities to incident command management. Unlike current practices reliant on second-hand accounts, this task empowers command management with firsthand situational awareness, facilitating more informed decision-making. UxV assigned to this task must possess rapid deployability, lightweight payloads, and the ability to operate continuously for extended durations. They must also offer unique imaging perspectives not readily available through human or manned aircraft reconnaissance. UAV such as outdoor quadrotors, blimps, or fixed-wing aircraft are ideal candidates for this task, with each platform offering distinct advantages in endurance and observational capabilities.

4. Decontamination Task:

The decontamination task entails the on-site decontamination of responders and civilians, which is crucial for mitigating the spread of hazardous substances. UxV assigned to this task is vital in setting up decontamination facilities and ensuring thorough and consistent decontamination processes. They offer the advantage of automating setup procedures and monitoring decontamination quality, enhancing response efficiency. UxV for this task must exhibit autonomous deployment capabilities and the ability to perform automated decontamination processes. They require sensors to assess decontamination quality and track individuals throughout the process. A team of UxV or a single versatile robot capable of transforming from a compact storage device into a functional decontamination system represents the most likely solution, offering flexibility and efficiency in response operations.

5. Hazard Disposal Task:

In the hazard disposal task, UxV are entrusted with the critical responsibility of removing, containing, or mitigating hazards, thereby minimising the impact of active threats during an incident. This task, rooted in the remove and eliminate hazard function, demands meticulous execution to safeguard lives and property. However, the success of this task hinges on UxV delivering clear benefits while minimising the risk of failure, as any lapses could erode the responder's trust. While UxV offer the advantage of keeping responders safely distanced from hazardous environments, ensuring their reliability is paramount. While high-stakes scenarios like defusing nuclear bombs underscore the need for unwavering reliability, UxV can still handle less extreme hazards like chemical leaks, provided they offer tangible benefits and robust performance. UxV assigned to this task must be engineered for reusability through effective decontamination. They must also feature versatile manipulators capable of handling diverse hazards efficiently. While deploying multiple specialised UxV may offer flexibility, it poses financial challenges for responders. Essential sensors such as imaging and location tracking enable UxV to assess and interact with hazards effectively, with optional sensors like microphones and thermal imaging enhancing hazard detection capabilities. UGV emerge as the preferred choice for this task due to their stability and suitability for hazardous environments.

Murphy et al. conducted a practical CTA based on high-fidelity field exercises at Disaster City, involving a Draganflyer™ X6 and an AirRobot® 100B small UAV for simulating a chemical train derailment. Their research involved 17 expert practitioners and instructors in CBRN, combining interviews, analysis, lessons from Fukushima, and a survey of hazardous material response literature. The Fukushima Daiichi nuclear emergency, a significant event, provided insights into the potential contributions of UGV and UAV-UGV teams in CBRN scenarios. Drawing from these experiments and research, they developed initial concepts for the utilisation of small, tactical UxV in hazardous material (HAZMAT) responses, encompassing ground, aerial, and marine platforms[10].

UAV Requirements and Considerations:

UAV serve critical roles in CBRN incidents, from wide-scale localisation to detailed material identification. However, they are typically launched from outside the Hot Zone, making direct line-of-sight piloting impractical. Continuous aerial surveillance becomes essential given the prolonged duration of CBRN incidents, which can extend from hours to days. This requirement favours UAV with extended endurance capabilities, such as fixed-wing configurations, allowing for prolonged loitering over affected areas. During a CBRN incident, identifying hazardous materials, their source, and quantity is paramount. This process typically requires around 20 minutes, emphasising the need for UAV capable of sustained monitoring. Helicopter-style UAV are preferred for their ability to fly low and close to the incident site, providing detailed observations while maintaining a stable position. Challenges related to UAVs in CBRN scenarios primarily revolve around sensing capabilities rather than endurance. Common concerns include the lack of sufficient optical acuity for reading labels and placards and isolating the source of leaks. Pan-tilt-zoom functionality is considered a minimum requirement to address these concerns. Additionally, issues such as image stabilisation, image enhancement to adapt to changing lighting conditions, and integrating infrared payloads for night operations are critical for effective UAV operations in challenging environments. Furthermore, responders express interest in UAV systems that can drop sampling motes, facilitating the collection of samples for analysis without direct human intervention.

UGV Requirements and Considerations:

UGV complement UAV by conducting indoor assessments and investigating materials from angles inaccessible to aerial platforms. In CBRN incidents, UGV are crucial for tasks such as mitigation, containment, and manipulation of hazardous materials. Challenges faced by UGV include the ability to reach the source from outside the Hot Zone, optical acuity for reading labels and placards, and the lack of image enhancement capabilities to adapt to varying lighting conditions. Like UAV, integrating infrared payloads for night operations and chemical sampling payloads is essential for comprehensive material assessment. UGV must also demonstrate the ability to operate in diverse environmental conditions, including water, mud, corrosive environments, and high-temperature settings. Features like door-opening mechanisms and decontamination systems are also critical for effective UGV deployment in CBRN scenarios.

Sensing Requirements and Considerations:

The sensor payload is a cornerstone of UxV capabilities in CBRN response. Besides high visual acuity and thermal sensing capabilities, the ability to accommodate plug-and-play sensor modules is essential for versatile and adaptable operations. Ensuring that each image is stamped with GPS location and orientation facilitates precise mapping and integration into larger situational awareness frameworks.

4.2 Practical Examples of the Development of Uncrewed Vehicles for CBRN Defence Tasks

Röhling et al. presented a research project for a CBRN hazard detection robot prototype for the German Military Forces. The design relied on the usage of commercially available sensors that could be exchanged and upgraded easily without touching the underlying robot platform.

The basic platform for the CBRN robot was the wheeled version of the QinetiQ Longcross with an additional Diesel power generator (see Figure 3). According to the manufacturer, the robot weighed about 340 kg and had a payload capacity of at least 150 kg. The compartment was made of carbon fibre and was environmentally shielded. While the compartment was sturdy enough to withstand small arms weapon fire, this was of no tactical significance because most military weapons had much higher piercing force.

The vehicle could reach a top speed of 4 m/s (approximately 14,4 Km/h) and had a battery capacity of about 30 minutes. The Diesel generator extended the runtime to approximately 90 minutes. The operational range was around 3000 m. The wheels on each side were rigidly connected to the gear mechanism, resulting in a very similar behaviour to a track drive, albeit with less traction. The robot could cope with rugged terrain and turn around on the spot. But as expected, the latter drew a substantial amount of motor current, significantly reducing the operation time.

The robot was equipped with several non-CBRN-related sensors to provide sufficient situation awareness. According to the manufacturer, the TopCon Legacy-E+ GPS receiver was able to receive both L1/L2 GPS and GLONASS satellite data with an RTK (OTF) accuracy below 25 mm. A rotatable camera provided visual feedback for the operator.

Depending on the mission parameters, different sets of sensors were required. Therefore, the sensor platform of the CBRN robot was constructed in a modular fashion so that it was possible to switch between different sensors. Figure 3 depicts the typical configuration for our robot. The large box on the left was the mobile detection system (MDS) sensor, designed to detect arbitrary radiation sources. Near the top was the identiFinder, another detector to identify radiological threats. At the bottom was a combination of two different chemical sensors, the MultiRAE+ and the LCD3.3.

Because of the modular setup, any sensor could be removed at any time to be used in a stand-alone mode. This allowed sensors to be used manually, should the need arise[11].

Figure 3: *The experimental CBRNE platform Kutusow. The metal boxes contain various CBRNE sensors which may trigger an alarm both locally and at the control station*[11]

Figure 4: *Kutusow encounters the suspicious gas emission*[11]

Several other efforts in developing CBRN systems underscore this topic's significance. For instance, the Canadian Armed Forces utilised a teleoperated all-terrain vehicle equipped with an integrated CBRN sensor suite, which is operated in conjunction with a ground station belonging to a remote mobile command post[12]. A key finding from this effort is the importance of proper training for prospective users. Similarly, Neilsen et al.[13] highlight the significance of robots in keeping humans away from hazardous environments. They enhance a purely tele-operated system by incorporating semi-autonomous features, thereby reducing the amount of training required for operators. Additionally, Jasiobedzki et al. introduced a system called Crime Scene Modeler to enhance operators' situation awareness. Its primary function is to construct a three-dimensional model containing points of interest such as CBRN substances[14]. A multi-quadrotor system, known as the Radiological and Imaging Data Enhanced Reconnaissance Swarm (RAIDERS), was developed by a multi-disciplinary team comprising 13 cadets and six faculty advisors from four different academic departments at West Point. This autonomous swarm of multiple quadrotor uncrewed aerial systems (UAS) was designed to conduct expedited radiation surveys. Additionally, the team utilised multiple fixed-wing UAS to provide live video overwatch of ground teams. The technology was adapted from research developed by the Defence Advanced Research Projects Agency (DARPA) for the 2017 Service Academy Swarm Challenge (SASC)[15].

Figure 5: *Field testing of the DARPA launcher and a ZephyrII fixed-wing sUAS at Range 11, West Point, NY*[15]

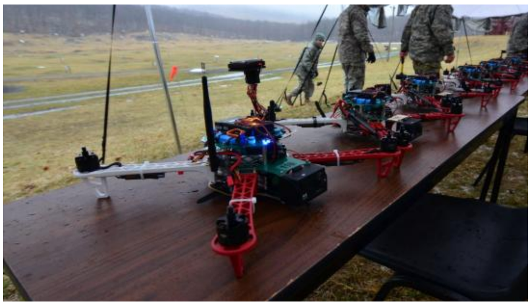

Figure 6: *F450 Flamewheel Quadrotor at USMA Range*[15]

The distributed control of UAS was facilitated by swarm behaviours implemented as Python scripts running onboard the UAS. These control algorithms used the SASC framework to access shared information among UAS over the WiFi network. They determined how agents would collectively distribute themselves and generated dynamically updated waypoints. These waypoints were then sent to the flight controller to navigate each aircraft accordingly. The quadrotor UAV systems modified by integrating radiation and altitude sensors onto them allowed to assist CBRN operators in expediting a forensics survey of post-nuclear blast debris fields. The system demonstrated the ability to configure and launch the swarm to improve response times rapidly. New swarm behaviours enabled the multi-UAS team to effectively distribute itself to provide a rapid initial survey and use that information to refocus a detailed survey around a location of higher interest. Finally, the data from the survey was fused and displayed in an interface available to CBRN operators in real-time[16].

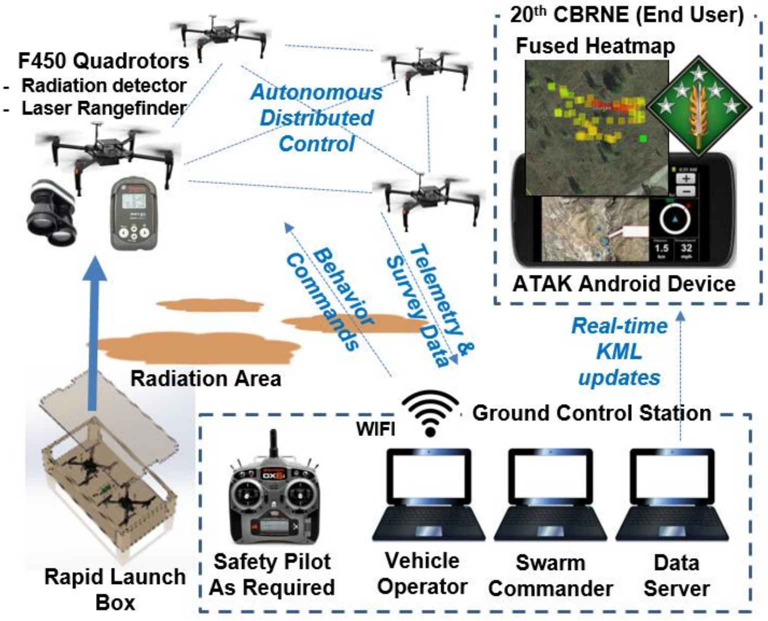

Figure 7: *System Architecture*[16]

5. Uncrewed Vehicles within Enabling Components of CBRN Defence

By Cdr. Manos LIONAS

For allied missions, NATO member countries must ensure appropriate CBRN expertise and manning through the command structure. The capability levels of CBRN defence are distinguished into basic, enhanced, and specialised capabilities. Basic capabilities ensure the survivability of the individual, enhanced capabilities enable the continuation of operations in a CBRN environment, and specialised capabilities ensure the qualified accomplishment of CBRN defence missions and tasks by specialised CBRN defence units. Therefore, NATO developed five enabling components covering all CBRN defence activities, which are the foundation for CBRN defence on operations[17]. These five enabling components are as follows:

1. Detection, Identification and Monitoring (DIM)
2. CBRN Knowledge Management (KM)
3. Physical Protection (PP)
4. Hazard Management (HM)
5. Medical Countermeasures (MedCM) and Casualty Care

Generally, UAV are often seen as having a more dominant role in CBRN defence due to their ability to cover large areas quickly and safely. They are particularly effective in the DIM enabling component of CBRN defence. UAV can carry a variety of sensors to detect and identify CBRN threats, providing real-time data and enhancing situational awareness. However, the role of UGV and uncrewed maritime vehicles (UMV) should not be underestimated. UGV are invaluable in hazardous environments for tasks such as decontamination and sample collection, while UMV can monitor and protect coastal areas against potential CBRN threats. The dominance of a particular type of UxV often depends on the specific scenario and mission requirements.

The folowing paragraphs focus on the UxV implication analysis of these five enabling components of CBRN defence.

5.1 Detection, Identification and Monitoring

UxV equipped with advanced sensors and sampling devices can play a crucial role in DIM of CBRN threats. For instance, UAV can cover large areas quickly, providing real-time data on chemical and radiological agents. Similarly, UGV can navigate challenging terrains to collect samples for further analysis[18]. This enhances the speed and accuracy of threat detection and minimises the risk to human operators.

Aerial survey for CBRN defence has seen a significant advancement in recent years. UAV equipped with CBRN sensors are being used for remote detection and monitoring of CBRN threats[19]. NATO's Combined Joint CBRN Defence Task Force has also incorporated an Aerial Radiological Survey capability, greatly enhancing the Alliance's defence against weapons of mass destruction (WMD) and CBRN threats. This capability allows for rapid and wide-area detection and identification of radiological threats[20].

However, despite these advancements, there are still challenges to overcome, such as ensuring the reliability of these systems in various environmental conditions, managing the large amount of data collected, and addressing cybersecurity risks. Ongoing research and development are expected to enhance aerial survey capabilities in CBRN defence further.

Sensor technology advances will improve these platforms' detection and identification capabilities. AI integration could enable UxV to autonomously analyse sensor data, identify threats, and make decisions. This improvement could significantly enhance threat detection and response speed and accuracy. However, these advancements will also require addressing cybersecurity, reliability, and regulatory challenges.

5.2 CBRN Knowledge Management

UxV can support CBRN KM through sensor integration, advanced modelling, simulation, and hazard prediction. The data collected by these platforms can be integrated into a centralised system, providing a comprehensive picture of the CBRN environment. This information can generate predictive models and simulations, aiding decision-making and strategic-operational level planning. Furthermore, UxV can provide real-time advice and updates, enhancing the overall responsiveness of the CBRN defence system.

CBRN knowledge management exploits UxV by collecting data from various sensors, which is then integrated into communication and information systems (CIS) for analysis and interpretation. This data can be used to provide CBRN advice, create advanced models and simulations, and predict hazards. For instance, UAV can provide real-time aerial surveillance data, which can be used to model the spread of a CBRN substances. UGV can collect ground-level data, providing detailed information about the local environment, while UMV can monitor maritime areas for potential CBRN threats.

CBRN sensors can be integrated into UxV in several ways. They can be mounted directly onto the vehicle or incorporated into its existing sensor suite. The integration process involves ensuring that the sensor can communicate with the vehicle's control system and that the data it collects can be processed and used effectively.

There are indeed significant constraints to overcome. One of the primary challenges is weight. CBRN sensors can be heavy, and too much weight can affect the vehicle's performance, particularly for UAV. Power consumption is another issue, as sensors can drain the vehicle's battery, reducing operational time. Environmental factors, such as temperature and humidity, can also affect sensor performance and must be considered.

The accuracy of a measurement with UAV can vary depending on several factors, including the quality of the sensor, the altitude at which the UAV are operating, and environmental conditions. It means that an exceptional performance and a unique utilization of UAV can be done by employing high-quality sensors and optimizing the operating conditions of UAV. It's also important to note that UAV data is often used with other information to understand a CBRN environment comprehensively.

Integrating CBRN sensors carried by UxV into operational Command and Control (C2) systems is a complex process involving several steps[21]. However, advancements in technology have made this process more feasible.

- Sensor Integration: The first step is to ensure that the CBRN sensors on the UxV can communicate with the C2 system. This typically involves using a standard data format or protocol.

- Data Transmission: The UxV must be able to transmit the data they collect back to the C2 system. This requires reliable and secure communication links.

- Data Processing: The C2 system must be able to process and analyse the data from the UxV. This can involve complex algorithms and may require significant computational resources.

- Data Presentation: Finally, the data must be presented in a way that is useful to the C2 system's operators and especially to the decision-makers. This could involve visualisations, alerts, or other forms of data presentation.

UxV can significantly enhance situational awareness in various ways:

- Data Collection: UxV, equipped with various sensors, can collect a vast amount of data from their environment. This includes visual data, thermal imaging, chemical readings, and more. This data can provide a comprehensive understanding of the situation at hand.

- Real-time Monitoring: These vehicles can monitor an area in real-time. They can be used to continuously patrol or observe a location, providing up-to-date information about any changes or developments.

- Accessibility: UxV can access areas that may be dangerous or impossible for humans to reach. This can provide critical information that would otherwise be unavailable.

- Analysis and Interpretation: Advanced UxV can analyse and interpret data that collects to identify potential threats or points of interest. This can help decision-makers understand the implications of the data more quickly and accurately.

- Communication: UxV can relay the information they gather to a central command centre or other units on the ground. This can ensure that all relevant parties have access to the same information, improving coordination and response times.

Figure 8: *Collaboration between Humans and Machines (CoHoMa)*[22]

UxV can help decision-makers make informed choices quickly and effectively, significantly improving situational awareness by providing comprehensive and real-time information about a situation.
AI and machine learning could enhance the capabilities of these platforms. AI could enable UxV to autonomously analyse sensor data, identify patterns, and make predictions. This could permit Allies to enhance the speed and accuracy of CBRN knowledge management. Furthermore, advancements in communication technology could allow for better coordination between multiple UxV, improving the overall effectiveness of CBRN defence missions. However, these advancements will also require addressing data security and privacy challenges.

5.3 CBRN Physical Protection

UxV can significantly enhance individual and collective protection in a CBRN environment and are currently used in CBRN defence for physical protection. They can transport and deploy protective equipment in contaminated areas, construct physical barriers, and monitor and protect areas against potential CBRN threats. By performing tasks that would otherwise put humans at risk, UxV contribute to safer and more effective CBRN defence[23].

Technology, particularly in advanced materials, will likely improve the capabilities of these platforms. For example, UxV could be equipped with new fabricated materials resistant to CBRN substances, enhancing their durability and effectiveness in a CBRN environment. Furthermore, integrating AI could enable UxV to perform the abovementioned tasks autonomously, improving physical protection's speed and efficiency.

Figure 9: *FLIR Centaur UGV*[24]

5.4 Hazard Management

UxV can also be used in CBRN defence for hazard management. They can assist with decontamination, hazard avoidance, hazard control, and waste management. For instance, UGV can be equipped with decontamination tools to clean contaminated areas, while UAVs can provide aerial maps for hazard avoidance. Additionally, UxV can help control hazards by isolating contaminated areas or deploying countermeasures. They can also transport hazardous waste to designated disposal sites, reducing the risk of further contamination.

As technological evolution will develop, these platforms' capabilities will also be enhanced. For example, UxV could be equipped with more advanced decontamination tools or waste management systems. The integration of AI could enable UxV to autonomously perform tasks such as hazard avoidance or control, improving the speed and efficiency of hazard management tasks.

5.5 Medical Countermeasures and Casualty Care

UxV can be vital for providing medical countermeasures and health care in CBRN scenarios. They can transport medical supplies to affected areas, evacuate casualties, and even perform remote health monitoring and diagnostics. This can significantly improve the speed and efficiency of medical response, potentially saving lives in critical situations.

For instance, UAV can deliver medical supplies quickly and efficiently to remote or contaminated areas. UGV can be used to safely evacuate casualties from a CBRN environment.

The medical field is developing so quickly that it will impact the mode in which UxV are exploited within this field. UxV could be equipped with more advanced medical equipment, allowing them to provide more comprehensive care in the field. AI could enable UxV to perform triage or medical diagnostics autonomously, improving the speed and efficiency of medical response.

6. Limitations of Uncrewed Vehicles in CBRN Defence

By Cdr. Manos LIONAS

UxV are invaluable assets in CBRN defence, offering the potential to mitigate risks to human life in contaminated or hazardous environments. However, these uncrewed systems have limitations and gaps despite their promising capabilities. Understanding and addressing these constraints is crucial for enhancing the effectiveness of CBRN defence strategies. The following paragraphs explore the challenges and shortcomings that UxV face in CBRN defence, ranging from technological constraints to operational limitations, thereby underscoring the need for continued innovation and development in this critical field.

6.1 Uncrewed Vehicles Constraints

- Technical Limitations: UxV rely heavily on technology, which can sometimes fail or malfunction. Issues can arise from software bugs, hardware failures, or communication disruptions.

- Environmental Factors: UxV may struggle to operate in harsh or complex environments. For example, heavy rain or snow can interfere with a UAV's flight, while rough terrain can impede a ground vehicle's movement.

- Data Overload: The vast amount of data UxV collects can be overwhelming and require significant storage, processing, and analysis resources.

- Security Risks: UxV can be vulnerable to hacking or cyber-attacks. If compromised, they could be used to cause harm.

- Regulatory and Ethical Issues: UxV raises several regulatory and ethical questions, particularly for military or defence purposes. These include concerns about accountability, privacy, and potential misuse[25].

- Cost: Developing, maintaining, and operating UxV can be expensive. This can be a significant barrier for many organisations.

6.2 Limitations of the Data Transmission of CBRN Sensors or Detectors Carried By Uncrewed Vehicles

- Distance: The range of data transmission can be a limiting factor. For instance, some remote sensor nodes used for CBRN monitoring can transmit data to a remote receiver up to 2 km away[26].

- Interference: Environmental factors such as weather conditions, physical obstructions, and electromagnetic interference can affect the quality and reliability of data transmission.

- Data Volume: The amount of data collected by CBRN sensors can be substantial, requiring significant bandwidth for transmission. This can be a challenge, especially for real-time monitoring applications.

- Power Consumption: Transmitting data, especially over long distances or at high frequencies, can consume significant power. This can be a concern for battery-powered UxV.

- Security: Data transmission can be vulnerable to cyber-attacks, including eavesdropping and data tampering. Ensuring the security of data transmission is a critical concern.
- Interoperability: The development of complex sensor networks often faces interoperability issues due to differences in data schemas, formats, and models in particular components[27].

These limitations must be considered when designing and deploying UxV for CBRN defence. While this process is not without challenges, ongoing advancements in areas such as data analytics, machine learning, and secure communications are making it increasingly possible to integrate UxV and their CBRN sensors into operational systems.

6.3 Environmental Effects on Operating Uncrewed Vehicles

The most critical constraint that limits further exploitation of UxV is arguably the technical challenge associated with operating in complex and harsh environments. A CBRN environment can be highly unpredictable and hostile, posing significant obstacles to the navigation, communication, and durability of UxV. For instance, high radiation levels can interfere with electronic systems, while chemical and biological warfare agents can corrode or otherwise damage the vehicle's materials. Overcoming these technical challenges requires advanced materials, robust system design, and sophisticated algorithms, all of which are ongoing research and development areas. Additionally, ensuring the security of these systems from cyber threats is another significant challenge that needs to be addressed.

Environmental factors limiting the use of UAV:

- Weather Conditions: Adverse weather conditions like heavy rain, snow, or high winds can affect the UAV's flight stability and operational range. These conditions can also interfere with the UAV's sensors, reducing their effectiveness in detecting and identifying CBRN substances.

- Terrain: While UAV are less affected by terrain than ground vehicles, certain landscapes can still pose challenges. For instance, operating in mountainous regions can be difficult due to altitude and wind pattern changes, or an operator can lose UAV from their line of sight.

- CBRN Contaminants: Exposure to CBRN substances can damage the UAV's materials and electronic systems. For example, corrosive chemicals can degrade the UAV's structure, while high radiation levels can interfere with its electronics.

- Temperature Extremes: Extreme temperatures, both hot and cold, can affect the performance and reliability of the UAV. High temperatures can cause overheating, while low temperatures can affect battery performance or increase the risk of icing, affecting flight performance.

- Visibility: Smoke, dust, or other airborne particles common in a CBRN environment can reduce visibility, making navigation more challenging and potentially interfering with the UAV's sensors.

These environmental factors need to be considered when designing and deploying UAV for CBRN defence to ensure their effectiveness and reliability. But despite these challenges, ongoing advancements in technology and policy are helping to mitigate them and unlock UxV's full potential in CBRN defence.

7. Evolution of Uncrewed Vehicles in CBRN Defence

By LTC Yann PERRON and MAJ Warren DEATCHER

Military technology development needs a balance. For example, elements of tank design must balance firepower, protection, and manoeuvrability. If you add too much to one element, you need an offset, such as adding more armour, which leads to more considerable power requirements, a bigger engine and a larger vehicle. Currently, the same challenges apply to autonomous systems, and achieving a balance between payload, manoeuvrability, protection, processing power, and size can only be completed on one platform with some degree of compromise. As has been described, there has been a growing application of autonomous or semi-autonomous systems on the battlefield for the last twenty years, as illustrated by the ever-increasing employment in the battle space through conflicts in Iraq, Afghanistan, Syria, Nagorno–Karabakh and Ukraine. UxV are becoming prolific due to their economic advantage in carrying out missions at a fraction of the cost of crewed solutions. The underlying motivation is to decrease costs, reduce manning, improve operational effectiveness, and reduce casualties. Technology may continue to keep them affordable, but to ensure their employability against new countermeasures, adding new technologies may also drive costs up. Nevertheless, given the operational advantages to both NATO and potential adversaries, there is a little doubt that robotic and autonomous systems will significantly and increasingly enhance, threaten, and enable current and future operational capabilities over the next 20 years[28].

7.1 The Effects of Emerging and Disruptive Technologies on Autonomous Systems

NATO continually examines what the battlespace may look like in the future through initiatives such as the Strategic Foresight Analysis and examination of science and technology trends, which includes an assessment of the effects of emerging and disruptive technologies (EDTs). NATO has identified that EDTs will present opportunities and challenges in an age where effects and enhancements converge across multi-dimensional environments[29]. These EDTs will significantly affect the employment of robotic and autonomous system (RAS) in the future, as well as creating a novel CBRN environment that will continue to balance emerging threats with technical solutions.

Emerging technologies are technologies or discoveries expected to reach maturity in the next 20 years which are not currently widely used or whose effects on Alliance defence, security and enterprise functions need to be clarified. Disruptive technologies are defined as those technologies or scientific discoveries expected to have a significant or revolutionary effect on NATO defence, security, or enterprise functions in 2023-2043[30]. EDTs balance the equilibrium of military technologies where some will assist in defensive capabilities while others will increase the threat environment. Identifying potential threats as early as possible is crucial to develop the concepts, doctrine and capabilities to defeat or mitigate those threats. "Technological developments will be increasingly intelligent, interconnected, decentralised and digital, " emphasising the future role of autonomous systems to include "military capabilities that will be increasingly autonomous, networked, multi-domain and precise." UxV future employment will likewise be both offensive and defensive.

7.1.1 Disruptive Technologies Likely to Affect Autonomous CBRN Systems

- Robotic and Autonomous Systems: RAS have been identified as an EDT. Autonomy is the ability of a system to respond to uncertain situations by independently composing and selecting different courses of action. Autonomy is characterised by degrees of autonomy ranging from fully manual to fully autonomous. Robotics is the study of designing and building autonomous systems spanning all levels of autonomy (including full human control). UxV may be remotely controlled by a person or act autonomously depending on the mission. Applications include access to unreachable areas, persistent surveillance, long endurance, robots in support of soldiers, cheaper capabilities, and automated logistics deliveries. SWaP-C (size, weight, power, and costs) reductions and significant improvements in onboard AI have made RAS an effective force multiplier in operations across the spectrum. The ultimate objective of integrating RAS into operations has always been to unite the human and autonomous system (at whatever level of independence) into a formidable team, allowing the automated system to take on dull, dirty, dangerous and dear tasks (the four D's of robotisation). This makes RAS ideal in utilisation for the employment and defence of CBRN materials.

- Big Data, Information and Communication Technologies: Big data will facilitate increased digitalisation and allow for advanced analytical methods to leverage large volumes of information. Big Data will lead to the potential proliferation of novel sensors and new communication modes, which will be optimised for potential applications through AI, enhanced modelling & simulation (M&S), information and communication technologies and sensor integration. Big Data will enable autonomous systems to collect, store and analyse significant amounts of data which will be incorporated into developing of an enhanced understanding of the operating environment. Big Data will assist with actualising a multi-domain C4ISR framework for the collection, processing, exploitation, and dissemination of information to support decision-making. Combined with other technologies such as AI and potentially quantum computing, it will allow for the incorporation of CBRN sensors with CBRN hazard warning and reporting that could instantaneously provide options for commanders on the ground.

- Artificial Intelligence (AI): AI refers to the ability of machines to perform tasks that usually require human intelligence – for example, recognising patterns, learning from experience, drawing conclusions, making predictions, or acting. AI enables autonomous platforms to navigate, detect objects and make decisions. The power of UxV has been amplified through AI integration with edge computing, allowing these machines to process vast amounts of data in real-time, make decisions, and adapt to changing environments without direct human operator intervention. UxV equipped with AI can scan areas, detect anomalies, and even engage in complex tasks like thermal imaging or CBRN sensors to define a hazard area, predict potential spread and define targets that may be susceptible to the effects of CBRN materials. Furthermore, the integration of AI has made swarm technology possible, where multiple UxV can operate in a coordinated manner, increasing the potential for adversary use of UxV with smaller payloads to achieve a larger area of effect. AI-enhanced UxV can improve the employment and definition of hazard areas by collecting atmospheric data and incorporating that data into advanced weather forecasting. The use of AI can also assist UxV defensive measures through the adaptive use of frequencies and bandwidth to minimise the effects of jamming[31].

- Energy and Propulsion: Energy and Propulsion consider the development of new generation, storage and propulsion technologies. Energy and propulsion will affect RAS's range and employment time, allowing for area sensing and continuous assessment of the operating environment.

- Electronic and Electromagnetic Technologies: Electronic and electromagnetic (E&EM) technologies are crucial in addressing the challenges faced by UxV in CBRN defence. The electromagnetic (EM) spectrum is becoming increasingly competitive and congested, posing a significant challenge for autonomous and counter-autonomous solutions, particularly in frequency management. However, new advancements in E&EM technologies offer improved operating space and protection from jamming efforts. Adaptive camouflage, for instance, will enhance UxV stealth capabilities by inhibiting UxV detection. Developing antennas for ultra-broadband emitters and receivers can provide resilient and secure communication channels for military operations, effectively countering current electronic warfare jamming capabilities. Additionally, progress in electromagnetism should lead to limiting and optimising electromagnetic emissions from UxV, significantly reducing or eliminating interference and the effects of enemy electromagnetic warfare. Optimising electromagnetic emissions could also improve battery life and increase operational ranges. These advancements pave the way for deploying UxV in swarms, enabling multidimensional and multicapacity operations. By leveraging these technological developments, UxV can achieve greater resilience, efficiency, and effectiveness in CBRN defence missions.

7.1.2 Emerging Technologies Likely to Affect Robotic and Autonomous CBRN Systems

- Quantum Technologies: Next-generation quantum technologies exploit quantum physics and associated phenomena at the atomic and sub-atomic scale, particularly quantum entanglement and superposition. These effects support significant technological advancements primarily in cryptography, computation, precision navigation and timing, sensing and imaging, communications, and materials. Quantum technologies supporting the employment of RAS include the development of Ultra-sensitive sensors through quantum sensing or using quantum communication to protect UxV from jamming. Quantum radar can make stealth technologies obsolete, provide more accurate target identification, and allow covert detection and surveillance.

- Materials and Advanced Manufacturing: Advanced novel materials are artificial materials with unique and novel properties. Advanced materials may be manufactured using techniques drawn from nanotechnology or synthetic biology. Development may include coatings with extreme heat resistance, high-strength body or platform armour, stealth coatings, energy harvesting & storage, superconductivity, advanced sensors & decontamination, bulk food production, fuel and building materials. New material development will find lighter, more durable, cost-effective solutions that are CBRN material resistant, easily decontaminable, or can incorporate stealth features. The use of 3D printing allows for potential sustainment and repair issues and creates challenges in the proliferation of CBRN materials.

7.2 The Employment of Robotic and Autonomous Systems to Support CBRN Defence

With the increasingly widespread use of UxV and swarms, research is ongoing to understand how to anticipate and defeat these threats through kinetic and non-kinetic means. Swarm-on-swarm engagement is an open area of study. It is clear from recent operations in Ukraine and elsewhere that improvement to counter-robotic and autonomous systems capabilities is an area that will need priority development over the next decade. Failure to counter ever cheaper and widely available UxV can and will have undesired strategic consequences.

Robots, the most promising evolution of UxV, can be exploited in CBRN defence. Indicatively we can consider the following implications:

- Detection and Identification: Robots can be equipped with sensors to detect and identify CBRN substances. This allows for quick and accurate detection without exposing humans to potential hazards.

- Sample Collection: Robots can collect samples from contaminated areas for further analysis. This reduces the risk to human operators and allows for more efficient sample collection.

- Decontamination: Robots can carry out decontamination procedures in contaminated areas, reducing the risk of human exposure.

- Surveillance and Reconnaissance: Robots can be used to monitor and survey areas for potential CBRN threats, providing valuable information for threat assessment and response planning.

- Medical Assistance: In the event of a CBRN incident, robots can assist with medical tasks such as casualty extraction and delivery of medical supplies.

- Logistics and Support: Robots can transport equipment and supplies in and out of a CBRN environment, reducing the risk to human operators.

By performing these tasks, robots can significantly enhance the effectiveness of CBRN defence missions while minimising the risk to human operators.

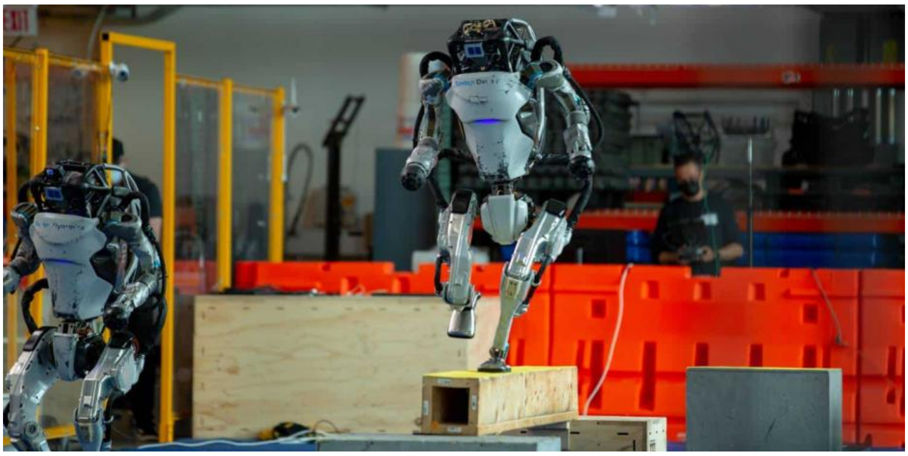

Figure 10: *Atlas performing parcour*[32]

Given the speed of the advancements autonomy achieves, it is well believed that autonomous uncrewed systems (AUS)* are going to revolutionise CBRN defence in several ways[33]: The main goals of implementing autonomy in UxV would be:

- Optimization of utilization with consequent cost reductions.
- Extended use of UxV without limitations induced by the operator´s natural constrainst.
- Improved safety by overcoming potential mistakes occured by the operator.

The employment of RAS to support CBRN defence in the future will also be aided by applying EDTs. As a counter to the potential threat from the employment of CBRN materials, EDTs may be used to assist in the counter/defeat aspect of CBRN defence against RAS threats.

With the employment of RAS, CBRN defence will be part of integrated military systems in the future. The future soldier will have a system of systems that allows him to detect, protect, define and delineate a CBRN threat immediately and autonomously. Autonomous systems will play a more significant role in achieving this. In the future operating environment, a soldier or a platform will be incorporated with sensors that detect a CBRN threat. Upon detection protective helmets will provide immediate protection to personnel. Sensors will be miniaturised to be easily carried on the person, providing this could include a variety of wearables from rings to watches. The detectors will be integrated with communications that will allow for the automatic transmission of CBRN reports. These reports will be incorporated into the hazard warning and reporting network and will advise other personnel of the threat. This will be displayed as part of the common operating picture combined with CBRN modelling to assist with planning. Once a threat is detected, the soldier or platform can launch UxV, which will delineate and confirm the hazard area, including physically and electronically marking the actual extent of the hazard area. To maintain momentum, decontamination UxV will deploy to commence decontamination tasks, medical countermeasures can be sent forward, and casualties can be extracted from the contaminated area and taken to designated casualty extraction zones. The increased use of UxV with ISR and precision strike platforms is increasingly common in operations. UxV could be employed with sensors to provide standoff detection, and electronic markers could be used to integrate hazard areas into the overall common operating picture. Using new sensors, materials, and propulsion will allow for autonomous platforms to support reconnaissance to detect and define the threat and combined with big data, support decision-makers in employing CBRN Defence Forces.

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*Note: If autonomy is integrated into UxV, the entire system is referred as Autonomous Uncrewed Systems (AUS).

Figure 11: *The Soldier of the Future*[34]

7.3 Defensive and Offensive Employment Considerations

Keeping a balance between the threat and countermeasures and counter-countermeasures for each advantage is offered through the application of EDTs on autonomous solutions and CBRN defence. Some EDTs can be used in support of offensive and defensive capabilities equally, such as:

- Effects of Weather and Climate. As previously highlighted, air-based autonomous platforms are susceptible to weather conditions. Weather conditions are a limiting factor in the use of agents affecting their employability to survive and be dispersed in the environment to achieve the desired effect.

- 3D printing and the development of new materials offer significant opportunities in CBRN defence by reducing logistical requirements and providing just-in-time sustainment, thereby lowering costs and making the deployment of RAS more economical. In the short to medium term, 3D printing could enable the production of disposable sampling and collection systems. This would limit production costs to operational needs and eliminate the need to decontaminate systems dedicated to CBRN samples. Integrating 3D printing into CBRN defence can address limitations associated with deploying systems in contaminated environments.

8. Assessment & Conclusion

By Lucie SEDLÁČKOVÁ, Cdr. Manos LIONAS and MAJ František GRMELA

This JCBRN Defence COE working paper comprehensively analyses the status, capabilities, and applications of UxV in CBRN defence tasks within NATO nations, partners and associated organisations. The integration of UxV in CBRN defence tasks significantly enhances operational capabilities across various domains:

- CBRN Reconnaissance: UxV equipped with advanced sensors, such as light detection and ranging, infrared cameras, and gas detectors enable swift detection, mapping, and identification of CBRN substances. They operate autonomously, minimising human exposure and allowing for prolonged and efficient reconnaissance missions.

- Aerial Radiological Survey: UAV equipped with gamma-ray detectors provide remote, accurate measurement of radiation levels, essential for emergency response and environmental assessment. Real-time monitoring capabilities enhance safety and operational efficiency.

- Biological Monitoring and Detection: UxV play a crucial role in collecting air samples and deploying biological sensors to detect biological threats in real-time. Integration with AI and machine learning enhances detection capabilities by analysing reconnaissance data.

- Decontamination: UxV assist in aerial surveys of contaminated areas, deliver decontamination agents precisely, and autonomously conduct decontamination tasks. This capability minimises risks to personnel and enhances overall operational effectiveness.

From the NATO CBRN defence perspective, it is essential to primarily focus on the role and influence of UxV on the five enabling components of CBRN defence. In particular, UAV play a crucial role in DIM because they can quickly cover large areas and provide real-time data. UAV with advanced sensors can detect and identify CBRN threats efficiently, while UGV can navigate rugged terrains to collect samples. UxV with CBRN sensors support CBRN knowledge management through data collection, integration and analysis. They provide real-time data, which can be used to generate predictive models and simulations and support decision-making processes. Despite challenges related to sensor weight, power consumption, and environmental factors, UxV enhance situational awareness and decision-making capabilities. UxV also enhance physical protection by transporting and deploying protective equipment, constructing barriers, and monitoring areas. They perform hazardous tasks that would otherwise put human operators at risk. In hazard management, UxV assist with decontamination, hazard avoidance, control and waste management. UGV can be equipped with decontamination tools, while UAV provide aerial maps for hazard avoidance. UxV are also vital in delivering medical countermeasures and healthcare in CBRN scenarios. They can transport medical supplies, evacuate casualties, and perform remote health monitoring and diagnostics. Despite challenges related to reliability, data management, and cybersecurity, integrating advanced sensor technologies and AI will further augment and enhance UxV capabilities in all enabling components of CBRN defence.

Even though UxV offer significant advantages in mitigating risk to human life and enhancing operational capabilities in CBRN hazardous environments, they are also subject to various technological and operational constraints. Understanding and addressing these challenges is critical for optimising the usage of UxV for CBRN defence tasks. Data transmission, influenced by distance, interference, data volume, power consumption, cybersecurity measures and interoperability, is included among technological and operational challenges. Technical limitations are represented by the reliability of UxV and data management issues, e.g., an insufficient data storage size. Moreover, UxV contrains can cover cyber-attacks, regulatory and ethical issues and expanses of their development, operation and maintenance. Lastly, it is important to stress environmental constraints, which might mainly influence operating UxV. Environmental limitations include weather conditions - affecting UAV flight stability and sensor effectiveness; terrain – rugged landscapes pose challenges for UGV, CBRN contaminants – exposure to hazardous agents can damage UxV; temperature extremes – can impair

UxV performance and battery life, and visibility conditions like smoke and dust reduce sensor effectiveness and complicate navigation.

NATO's initiatives, such as the Strategic Foresight Analysis and examination of science and technology trends, highlight the transformative impact of EDTs on future battlespaces. These EDTs present both opportunities and challenges, significantly influencing the employment of RAS and creating a novel CBRN threat environment. Identifying and addressing potential threats early is crucial for developing effective defence strategies. By leveraging EDTs, such as RAS, Big Data, AI, and quantum technologies, NATO can enhance its operational capabilities, ensuring effective and efficient responses to CBRN threats. However, the dynamic nature of these technologies requires continuous innovation and adaptation to maintain a strategic advantage. Addressing technological limitations, cybersecurity risks, and operational integration challenges is essential for maximising the potential of EDTs to safeguard against future CBRN threats. Through strategic investment and development, NATO can ensure robust defence tactics, techniques and procedures, enhancing its forces' safety and operational continuity in increasingly complex threat environments.

Despite the potential benefits, the survey highlights that over 60% of NATO nations do not currently utilise UxV for CBRN defence tasks. However, ongoing research and development efforts, such as the CBRN SaaS project under the EDA/EU umbrella, indicate a strong commitment to integrating UxV into operational frameworks. Integrating UxV into the CBRN defence tasks provides critical and real-time data. It enhances situational awareness, allowing responders to assess and mitigate hazards more effectively while minimising human exposure to dangerous environments. As written in Chapter 4, research and development efforts focus on understanding the cognitive and operational requirements of deploying UxV in CBRN scenarios and identifying specific tasks where these technologies can be most effective and beneficial.

In conclusion, this JCBRN Defence COE working paper has thoroughly examined the status, capabilities, and application of UxV in CBRN defence tasks across NATO nations, partners, and associated organisations. The employment of UxV in CBRN defence offers significant advancements in CBRN defence capabilities, substantially enhancing operational efficiency while minimising risk to personnel operating in the CBRN environment. However, it is also highlighted that despite their potential, a significant portion of NATO nations have not yet fully integrated UxV into their CBRN defence strategies. This underscores the need for continued research, development, and investment in these technologies, particularly in overcoming challenges related to reliability, data management, cybersecurity and environmental factors. Moreover, the dynamic nature of EDTs necessitates continuous innovation to maintain a strategic advantage in CBRN defence.

NATO's focus on integrating EDTs such as Big Data, AI, and autonomous systems, further emphasises the transformative potential of UxV in future battlespaces. By addressing existing technological and operational constraints and strategically investing in these advanced technologies, NATO can enhance its defence posture, ensuring robust and effective responses to CBRN threats in increasingly complex and challenging environments. This comes hand to hand with the offensive capabilities that UxV can offer to adversaries. Alliance should establish an interdisciplinary and innovative approach to counter the dormant threats that UxV will introduce in the future operating environment. Stronger cooperation between JCBRN Defence COE and Integrated Air and Missile Defence COE (IAMD COE)[*] will pave the way for generating synergies for countering autonomous systems operating in air domain. Further cooperation can be established with other stakeholders such as the Maritime Security (MARSEC COE), NATO Maritime Interdiction Operations Training Center, the Centre for Maritime Research and Experimentation, Crisis Management and Disaster Response COE to identify areas of cooperation and establish a structured collaboration that will offer converging effects for the Alliance. Concurrently, this emerging UxV phenomenon is to be incorporated into the relevant Alliance's doctrines and publications related to CBRN defence.

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[*] Note: Integrated Air and Missile Defence COE is in Chania, GREECE. Its focus areas are Surveillance, Offensive / Defensive Options in Support of Integrated Air and Missile Defence, Technical and Procedural System Integration, Counter Rocket, Artillery and Mortars (C-RAM), Passive Air and Missile Defence, IAMD's role in Anti Access / Area Denial (A2/AD), Countering Unmanned Aerial Systems (C-UAS). For more information visit *https://iamd-coe.org/*

Annex: Industry Data Sheets

By Lucie SEDLÁČKOVÁ

The following data sheets provide examples of UxV involved in CBRN defence, detailing their technical features to enhance reader comprehension.

NUVIATECH INSTRUMENTS – DRONES-G MINI MODULE

Technical Specifications

Dimensions	250 x 110 x 110 mm
Weight	1.125 kg (with holder for DJI 300 RTK)
Battery	Li-Poll, 11.1 VDC/500 mAh, duration max 1,5 hour
Detector 1	NaI(Tl) Ø 1" x 2", 1" photomultiplier • FWHM < 7.5% @ 661 keV • 50 nGy/h to 80 µGy/h
Detector 2	GM tube LND 71210 • 50 nGy/h to 20 mGy/h • 1.4 cps @ 1 µGy/h, 137Cs
Altimeter	Optical rangefinder, max. 50 m
Operating temperature	-30 to + 55°C
Communication	Radio, 433 MHz, range max. 3 km
Software	Dronic Lite

A recommended platform for use of this module is any UAV with sufficient payload.

SCHIEBEL – CAMCOPTER S-100

Technical Specifications

Dimensions	3110x1120 mm (main rotor diameter: 3400 mm)
Weight	110 kg (Payload Capacity 50 kg)
Propulsion	Fuel: Internal tank – 57 l External tank – 25,4 l
Detector	Up to requirements
Endurance	>6 h with 34 kg payload plus optional External fuel tank extending endurance to >10 h
Data Link Range	Up to 200 km (108 nm) available
Dash Speed	100 kn (185 km/h) IAS
Loiter Speed	55 kn (102 km/h) for maximum endurance

DOK-ING – MVC – 8 KOMODO

Modular Hybrid System for Extreme Environments

Technical Specifications

UGV lenght	Max 10 000 mm
Weight	25 000 kg
Propulsion	Diesel engine/generator Battery cappacity: 70 kWh Diesel fuel tank: 150 l Charger: 10 kW
Endurance	Protection aginst hich and low temperatures Maximal speed: 20 km/h
Detector	Chemical detector IAW NATO STANAG 4701 (1) AEP-75-Ed.: A Ver. 1 Radiological detector IAW NATO STANAG 4701 (1) AEP-75-Ed.: A Ver. 1
Other devices	Sampling system IAW NATO STANAG 4701 (1) AEP-66 (A) (1) Decontamination robotic arm for surfaces, vehicles and equipment Decontamination capacity: 1500 m^2/hr, 10 vehicles/hour

Authors

Lucie SEDLÁČKOVÁ joined the JCBRN Defence COE in January 2017 as a member of the Transformation Support Department, and she is assigned to the Experimentation Specialist position. She graduated from the University of Pardubice in 2012, focusing on chemical and biological sciences, particularly immunology. During her career in the military environment, she has supported NATO concept development and experimentation activities and has also participated in the NATO Science and Technology Organisation project orientated on Biotechnology in CBRN Defence.

CDR Manos LIONAS has been a member of the JCBRN Defence COE since August 2022 as the Joint Doctrine Specialist. He graduated from the Hellenic Naval Academy in 1998 as an Engineer Officer. His operational career included various types of surface war ships. Additionally, he specialized in naval aviation maintenance with 10 years' experience. His main interest in CBRN defence is at the operational level as custodian of AJP-3.8, Allied Joint Doctrine of CBRN Defence.

LTC Yann PERRON joined the French Forces in 1996 as an Engineer paratrooper and then an infantry officer. In 2009 he joined the CBRN domain in the 2nd Dragoon regiment, in which he had been notably deputy Chief of Staff, then in the French Joint CBRN Centre in which he was responsible for the Land Force CBRN doctrine. In 2022, he had been appointed as Lessons Learned Specialist at the JCBRN Defence COE. He holds a bachelor's degree in Physic-chemistry and a master's degree in Nuclear Physics. He had been deployed 8 times abroad and 7 times for antiterrorist missions, notably as G3 chief, TOC chief and CBRN expert.

MAJ Warren DEATCHER joined the JCBRN Defence COE in June 2022 and has been serving as the Operations Planning Support Section Chief providing CBRN planning support at the strategic and operational level. He is a Canadian Armoured Officer from the Lord Strathcona's Horse (Royal Canadians) with 39 years of service. He has spent the last 22 years working across the spectrum of CBRN activities including Force Protection, Counter Terrorism, Counter Weapons of Mass Destruction, and Consequence Management. He has extensive experience in civil-military cooperation and spent five years as the military liaison officer to the Royal Canadian Mounted Police. He has developed a myriad of CBRN plans to support Canadian Armed Forces operations and contingencies domestically and around the world.

MAJ Bruno FERRANDES joined the Italian army in 1997 as a paratrooper. After his graduation from Non-Commissioned Office Academy Program, he served as a platoon commander and experienced 2 deployments to Afghanistan under the ISAF mission and one to Bosnia. In 2007, he was assigned to the CBRN School in Rieiti (ITA) as a commander of CBRN company and he was deployed to Afghanistan as a CBRN specialist 2 times. MAJ Ferrandes joined the JCBRN Defence COE in September 2002 as a Section Chief of Defence Planning and Capability Development. Since September 2024, he has been assigned to the NATO Rapid Deployable Corps Italy.

MAJ Miroslav LABAŠKA is a highly skilled scientist with a strong background in organic synthesis and forensic chemistry. He holds a PhD in nuclear chemistry and has devoted his academic and professional career to modernizing and advancing CBRN capabilities. With 17 years of experience as a military officer, he has been instrumental in the development of advanced technologies and strategies to enhance CBRN defence. His contributions make him a key figure in the intersection of science and defence.

MAJ František GRMELA joined the JCBRN Defence COE in September 2019. He is a Lessons Learned Analyst Evaluator. He graduated Military University of Technology Liptovský Mikuláš (SVK) in 1992. His specialization was Aircraft and Missile Technology. In his career, he has been instrumental in the development of advanced technologies and strategies to enhance CBRN defence. His contributions make him a key figure in the intersection of science and defence.

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