

New technologies to address explosive hazards in Africa

Institute for Security Studies and the International Committee of the Red Cross



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Preface

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Executive summary

In 2025, there have been significant reductions in funding for humanitarian mine action (HMA) globally, with African programmes particularly affected, and future budgets likely to shrink further. This monograph analyses how Africa's response to landmines and other explosive hazards could be enhanced through practical applications of technology: airborne remote sensing and data processing using deep-learning artificial intelligence models. These tools, especially when deployed for detection activities, have the potential to greatly accelerate land release and improve operational efficiency.

The purpose of this monograph is to identify and evaluate opportunities for the introduction of new technology for reducing explosive hazards in Africa. The focus is on how new technology can help develop African states' HMA capabilities. The monograph recognises that various types of explosive hazards pose significant threats, including mines, explosive remnants of war resulting from conflict, the widespread use of improvised explosive devices by non-state armed groups, and accidental explosions at ammunition storage sites.

This monograph analyses how Africa's response to landmines and other explosive hazards could be enhanced through practical applications of technology

The monograph reviews the applicability of visible-light camera systems, thermal imaging, light detection and ranging and unmanned aerial vehicles for explosive hazards. It also examines the suitability of non-explosive tools, binary liquid explosives and explosive harvesting as potential technologies for ordnance disposal. Finally, it highlights the essential role of data analysis tools to automatically process large volumes of sensor-generated data to increase detection probability and reduce false alarms.

The monograph starts with a review of the principal explosive hazards that may be encountered in Africa and provides an overview of the threats they pose. It goes on to examine the major normative frameworks that shape HMA in Africa: the Anti-Personnel Mine Ban Convention, the Convention on Cluster Munitions and the Convention on Certain Conventional Weapons. It then explores the impact

of International Mine Action Standards and National Mine Action Standards. In the Africa context, the monograph provides an overview of the Common African Position on Landmines and the African Union Post-Conflict Reconstruction and Development Policy. It examines the utility of unmanned aerial vehicles and remote sensing for HMA. The issue of data deluge is addressed and options for the use of deep-learning algorithms and artificial intelligence are discussed. The monograph also explores innovative approaches to the disposal of explosive ordnance, given the frequent scarcity of serviceable explosives.

The final section summarises the candidate areas for technology insertion. It examines the key requirements and constraints affecting the acquisition of new technologies for use in HMA programmes in African Union states and discusses issues of technology readiness, affordability, sustainability and regulatory and legislative issues.

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Acronyms

AI	Artificial intelligence
APMBC	Anti-Personnel Mine Ban Convention
ASA	Ammunition storage area
AU	African Union
CAPL	Common African Position on Landmines
CCD	Coherent change detection
CCM	Convention on Cluster Munitions
CCW	Convention on Certain Conventional Weapons
EHS	Explosive harvesting system
ERW	Explosive remnants of war
GNSS	Global navigation satellite system
GPR	Ground-penetrating radar
HE	High explosive
HMA	Humanitarian mine action
ICRC	International Committee of the Red Cross
IED	Improvised explosive device
IHL	International humanitarian law
IMAS	International Mine Action Standards
ISS	Institute for Security Studies
LiDAR	Light detection and ranging
NGO	Non-governmental organisation
NMAS	National Mine Action Standards
NSAG	Non-state armed group

NTS	Non-technical survey
PCRD	Post-conflict reconstruction and development
SAR	Synthetic aperture radar
TRL	Technology readiness level
TS	Technical survey
UAS	Unmanned (or uncrewed) aerial system
UAV	Unmanned (or uncrewed) aerial vehicle
UN	United Nations
UNMAS	United Nations Mine Action Service
UXO	Unexploded ordnance

Chapter 1

Context

In 2025, there have been significant reductions in funding for humanitarian mine action (HMA) globally, with African programmes particularly affected, and future budgets likely to shrink further. This monograph analyses how Africa's response to landmines and other explosive hazards could be enhanced through practical applications of technology: airborne remote sensing and data processing using deep-learning artificial intelligence (AI) models. These tools, especially when deployed for detection activities, have the potential to greatly accelerate land release and improve operational efficiency.

The study used a qualitative approach, combining primary and secondary data collection techniques and tools. An extensive literature review was conducted to gather secondary data and develop a thorough understanding of the state of mine action globally and across the African continent. Particular attention was paid to opportunities and risks associated with technology use in HMA. The review examined practical experiences in the use of airborne remote sensing and AI from which the International Committee of the Red Cross (ICRC)–Waseda programme could learn.¹

Since the research sought to explore avenues for mainstreaming technologies and examine African states' mine action strategies, it was crucial to complement the study with primary data. Key stakeholder consultations were conducted in Ethiopia, Nigeria and Senegal to accurately assess contamination, explosives' impact on human security, challenges in responses and opportunities for using technologies. This monograph also draws on evidence from elsewhere in Africa, where appropriate.

Purpose of the monograph

The primary purpose of this monograph is to identify and evaluate opportunities for the introduction of new technologies for explosive hazard mitigation in Africa. The focus of the monograph is on how new technology can help in the development of states' HMA capabilities to address explosive hazards from landmines, explosive remnants of war (ERW) resulting from conflict, the extensive use of

improvised explosive devices (IEDs) by non-state armed groups (NSAGs) and the consequences of accidental explosions at ammunition storage areas (ASAs).

Overview of the monograph

Explosive hazards in Africa

This opening section provides an overview of the principal explosive hazards that exist in Africa today including landmines and ERW, IEDs and both deliberate and accidental explosions at ASAs.

Normative frameworks

The section on normative frameworks reviews the application of the principal conventions and protocols in Africa and includes the Anti-Personnel Mine Ban Convention (APMBC), the Convention on Cluster Munitions (CCM) and the Convention on Certain Conventional Weapons (CCW) – Protocols II and V. This section also reviews the application of International Mine Action Standards (IMAS) and the development of National Mine Action Standards (NMAS). It concludes with a review of the African context and covers the Common African Position on Landmines (CAPL) and the African Union (AU) Post-Conflict Reconstruction and Development (PCRD) Policy.

Technological developments

This section starts with a review of the principal capabilities and gaps in the detection and safe disposal of explosive hazards and includes manual detection, biological detection, mechanical clearance and the disposal of landmines, ERW and IEDs. It then looks at how new technology can be applied to explosive hazard detection and disposal. This section then provides a contemporary overview of the utility of unmanned aerial vehicles (UAVs), remote sensing and related data analysis.

The subsection on remote sensing technologies reviews several technical approaches that may be employed in the field of explosive hazard detection, including visible light camera systems, thermal imaging, light detection and ranging (LiDAR), synthetic aperture radar (SAR) and electromagnetic sensing. Finally, it covers ground-penetrating radar (GPR), a technology that provides the capability to detect explosive ordnance or IEDs with low or zero metal content.

The final subsection on data analysis examines the options available for the processing of the data generated by modern remote sensing technologies. It examines the groundbreaking work conducted by Professor Hideyuki Sawada's team at Waseda University in Japan on advanced GPR applications in HMA.

Candidate areas for technology insertion

This concluding section highlights the principal areas where technology insertion could take place in Africa to improve the outcomes of HMA and explosive ordnance hazard mitigation programmes.

Who can benefit from this monograph?

This monograph is intended for use by:

- Senior government officials, especially in defence and interior ministries developing explosive hazard policy and regulations
- Foreign affairs staff reporting on treaty obligations, e.g. APMBC, CCM, CCW Protocols II and V
- Officials and organisations involved in capability development for explosive threat mitigation
- Donors supporting explosive hazard reduction efforts in Africa
- Operational and technical practitioners implementing HMA programmes

Chapter 2

Explosive hazards in Africa

Through generations, since humanity developed firearms and explosives, weapon contamination has been among the most persistent legacies of war. Successive armed conflicts, international and non-international alike, across the world have led to the widespread use of explosives, causing harmful effects that can last for decades after hostilities end.² Conventional landmines, ERW and, in rare cases, chemical, biological, radiological and nuclear weapons have been significant sources of contamination.³ More recently, IEDs – most often victim-operated – have lengthened the list of lingering contaminants.⁴

As vast swathes of land become gangrenous with these explosives, human security is dangerously at stake. While some are killed or maimed, thousands more are deprived of essentials for survival.⁵ Explosive ordnance poses a particular hazard to internally displaced people and migrants as they are unlikely to be familiar with weapons contamination in areas of displacement or new contamination in areas of return. Access to income sources such as farming, intercity and cross-border commerce is considerably disrupted, given that exploiting farmlands and navigating routes has become highly hazardous. Essential public services, including healthcare, education and water supply, become unavailable as people's mobility is restricted.

Africa has been and remains significantly affected by landmines, ERW and IEDs, primarily as a legacy of past and ongoing conflicts in regions such as the Sahel, the Horn of Africa and parts of central and southern Africa. In 2023, 24 African contexts recorded explosive ordnance-related casualties; other continents registered fewer countries affected.

In 2023, Nigeria (343), Burkina Faso (308), Mali (174) and Ethiopia (106) were among the top 10 most affected countries worldwide by number of victims.⁶ Countries including Angola, Burkina Faso, the Central African Republic, Cameroon, Chad, the Democratic Republic of the Congo, Eritrea, Ethiopia, Libya, Mali, Mauritania, Morocco, Mozambique, Nigeria, Senegal, Somalia, Sudan, South Sudan and Zimbabwe⁷ continue to face widespread contamination. While many states have made substantial progress in mine clearance and victim assistance, new contamination from IEDs, particularly in conflict zones involving NSAGs, has

emerged as a growing threat. In recent years, the use of UAVs and first-person-view drones has added an extra dimension to explosive hazards.

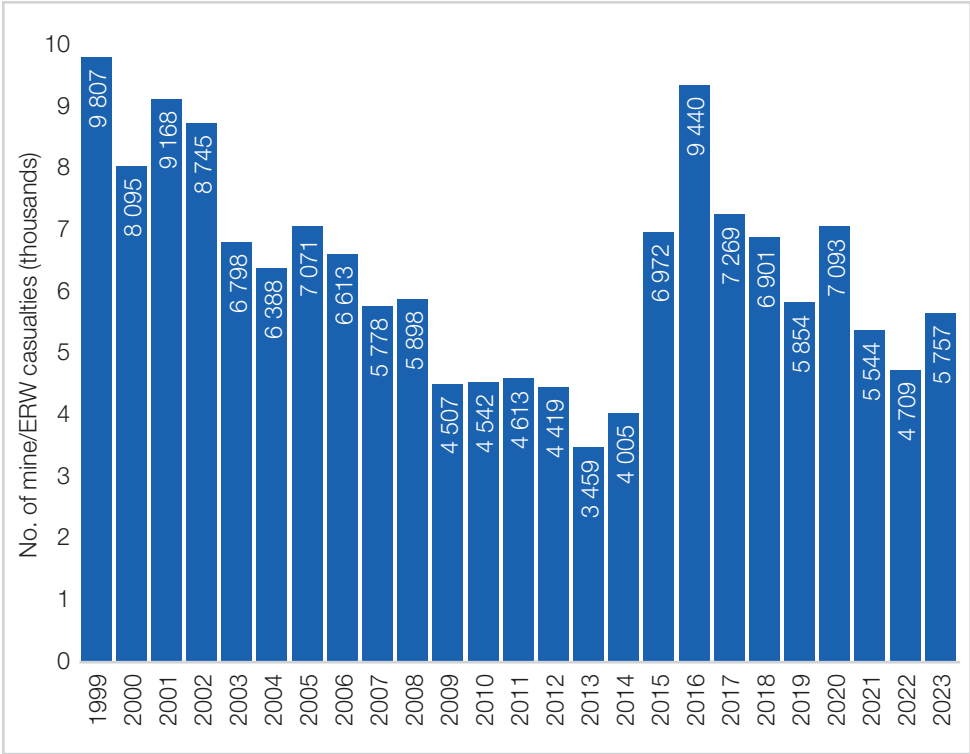
As clearance is a lengthy and costly activity, affected areas often remain polluted for decades, with significant consequences for displacement and development in the region.

Landmines and explosive remnants of war

Landmines and ERW (made up of unexploded and abandoned ordnance) land contamination affect over half of the world’s countries.⁸ The millions of people killed, deprived and forced to live in fear daily have made weapon contamination a global crisis that requires a coordinated response. Over the last eight decades, states, humanitarians and affected communities have separately or collectively intensified efforts to address this worldwide challenge.

In 2023, there was an increase in globally recorded casualties caused by landmines and ERW. A total of 5 757 people were killed or injured representing a 22% increase (1 048) compared to 2022. The real figure is likely to be significantly higher as many accidents and casualties go unreported. The chart below shows casualties caused by landmines and ERW from 1999–2023.⁹

Chart 1: Global landmine and ERW casualties by year, 1999–2023



Source: International Campaign to Ban Landmines

The challenges posed by landmines and ERW is immense, especially in Africa. While much of the weapon contamination is decades-old, ongoing conflicts in the Democratic Republic of the Congo, Sahel, Lake Chad region, Sudan and Somalia, among others, see continuous additions. Furthermore, UAVs with guided air-to-surface munitions have been widely employed in the Sahel and across the Horn of Africa. Their usage often ends up as ERW, adding to existing contamination. Chart 2 shows a Bayraktar TB2 UAV armed with a laser-guided MAM-C and MAM-L in Libya in February 2021.

Chart 2: Bayraktar TB2 unmanned combat aerial vehicle, Libya



Image credit: Military Africa

Libya provides a useful example of how landmine contamination can build up over many decades if residual contamination is not addressed in a timely fashion. Current landmine contamination in Libya relates to conflicts that ended decades ago. During World War II, landmines were laid in large numbers by German, Italian and British forces. In May 2003, it was estimated that between 1.5 million and three million landmines from that period remained in Libya.¹⁰ An additional two million mines were reported to have been laid during the period of the Libya–Egypt war of 1977.¹¹

Landmines were also used extensively in southern Libya and the Aouzou Strip in Chad during the periods of conflict between Chad and Libya from 1978–1987. More recently, during and after the 2011 Libyan Civil War, Libyan forces laid protective perimeter minefields around several ASAs. In 2014, it was also established that landmines, probably acquired from former government ASAs, were used in the

vicinity of Tripoli International Airport. Landmines deployed during and since the civil war were typically scattered, and no definitive minefield records were kept.

Senegal offers another example of the challenges posed by landmines and ERW on the continent. Its ongoing struggle stems primarily from the longstanding violence in Casamance since 1982. Although the conflict's intensity has decreased, not all areas are accessible. Thus, demining operations occur in limited spaces in areas under army control and zones where agreements with NSAGs have been reached.

Since the first explosive-related incident in 1988, a total of 870 casualties, including 610 civilians, had been recorded in Senegal as of December 2024. On 1 September 2006, an ICRC delegate was killed and two colleagues seriously injured when the vehicle in which they were travelling struck a suspected anti-vehicle mine.

Improvised explosive devices

An IED is most commonly defined as:

A device placed or fabricated in an improvised manner incorporating destructive, lethal, noxious, pyrotechnic or incendiary chemicals and designed to destroy, incapacitate, harass or distract. It may incorporate military stores but is normally devised from non-military components.¹²

IED types are often classified by counter-IED specialists by function:

- Command-initiated IEDs are devices triggered at a specific moment chosen by the user. They can be activated using various methods, such as radio signals, command wires, pull mechanisms or projectile control.
- Time-operated IEDs are intended to detonate after a set delay. This delay can be implemented using mechanical, chemical, electrical or pyrotechnic mechanisms.
- A victim-operated IED is triggered by the unintentional actions of an unsuspecting person. It relies on the target performing a specific action that triggers the device. Common activation methods include pressure plates, tripwires, light sensors, movement triggers, collapsing circuits and anti-lift mechanisms.
- A projected IED is a device launched from a makeshift baseplate designed specifically to penetrate or bypass perimeter security defences.
- A suicide IED is a device detonated by the attacker at a time of their choosing with the intent to kill themselves as part of the attack or to avoid capture.

The IED is not a new threat; it has a long history of use in high-profile political assassinations, including the killing of Tsar Alexander II in 1881, the attempted assassination of Adolf Hitler in 1944, the murder of Spanish Prime Minister Luis Carrero Blanco in 1973 and the assassination of Indian Prime Minister Rajiv Gandhi in 1991.

In the period 2011–2020, IEDs were responsible for at least 135 800 civilian casualties, exceeding those caused by manufactured explosive ordnance.¹³ However, it is also important to look past the numbers.

Behind these statistics lie unquantifiable personal experiences of suffering, terror, and bereavement through death, injury, and loss of livelihoods. Untold numbers of people who live and work in IED-affected areas – be they security forces, peacekeepers, or civilians – experience day-to-day stress and fear of sudden death or injury, and associated mental and physical health impacts.¹⁴

Some IEDs fall within the scope of the APMBC when they meet the definition of an anti-personnel mine under Article 2(1), that is, a mine designed to be detonated by the presence, proximity or contact of a person.¹⁶ Practically, this means that many victim-operated IEDs, or other types of IEDs that contain a victim-operated mechanism, may be considered anti-personnel mines under the provisions of the APBMC. If so, they would be subject to the same restrictions as those of manufactured landmines for states parties to the APMBC. That their usage is often employed by NSAGs adds an additional layer of complication.

In many areas of Africa, the principal threat posed by explosive ordnance has migrated from conventional explosive ordnance and landmines to IEDs

The threat posed by IEDs in Africa is considerable and increasing. The ready availability of substantial quantities of high explosives from conflict zones (looted from ASAs and lifted from minefields) has resulted in the widespread use of military munitions as the main charge for IEDs. In many areas, homemade explosives have been made from easily accessible explosive precursors. In areas where commercial mining is taking place, commercial explosives have also been employed within IEDs.¹⁵

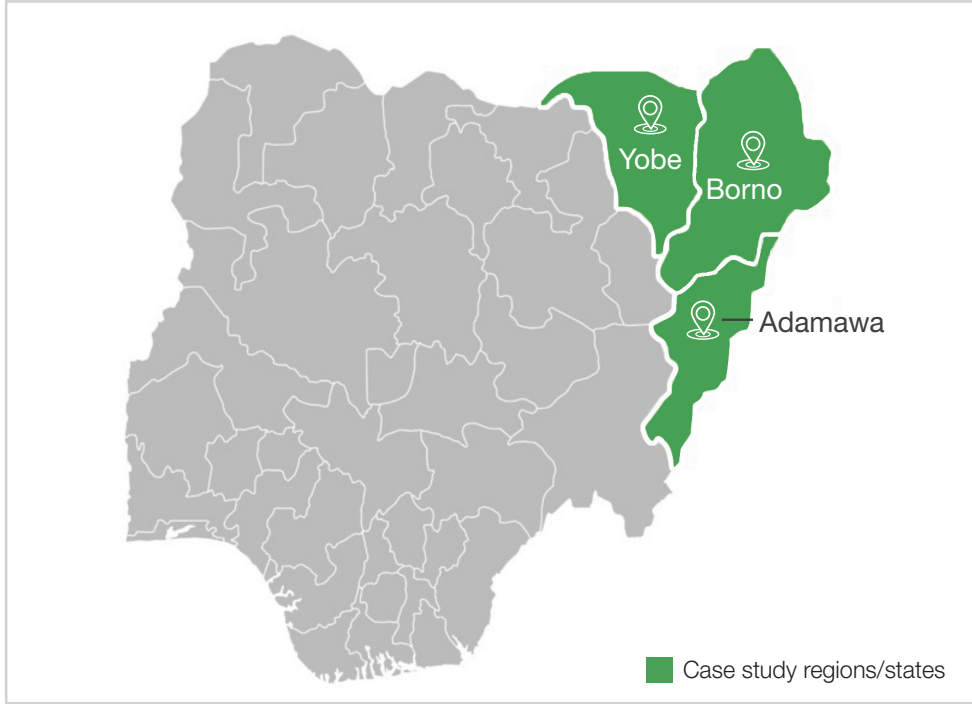
In many areas of Africa, over time, the principal threat posed by explosive ordnance has migrated from conventional explosive ordnance and landmines to IEDs. IEDs have been used extensively by NSAGs and are currently considered the weapon of choice in countries such as Burkina Faso, Central Africa Republic, Mali, Nigeria and Somalia. IEDs have also been used in conjunction with conventional explosive ordnance in Libya, Sudan, Ethiopia and Kenya. The massive use of IEDs throughout regions like the Central Sahel and the Horn of Africa is gradually limiting the progress made in decontaminating African countries.

An example of IED use in Africa can be seen in Nigeria, which has grappled with landmines and ERW since the 1967–1970 Biafra War in its southeastern region. The conflict left vast areas contaminated with conventional landmines and ERW, but Nigeria had made significant progress in their clearance until the late 2000s.¹⁷ As the country was poised to celebrate its gains, Boko Haram’s uprising in the early 2010s brought new explosive-related challenges.

Nigeria’s contamination has shifted from conventional landmines to a dire confrontation with IEDs, widely spread across its northeastern region. In the most heavily affected states, Borno, Adamawa and Yobe (see Chart 3), various types of IEDs are used. The majority employ main charges acquired from explosives harvested from ERW or rely on homemade explosives made from commonly available agricultural fertilisers.

NSAGs’ generalised use of IEDs and the spread of ERW have had severe impacts on Nigeria’s human security. Vast areas of previously untouched arable land and farmland have been contaminated, jeopardising food security in the region and, to some extent, across the country. According to government sources, improvised landmines and ERW have caused significant harm to civilians. As of September 2024, official sources reported 613 casualties in northeastern Nigeria. Consultations with humanitarian actors indicated that civilian victims accounted for 64% of the total.¹⁸

Chart 3: Nigeria – regions most affected by IEDs



Weaponised unmanned aerial vehicles

A recent development has been the introduction of weaponised UAVs into conflict zones such as Mali, Libya and Sudan. The ready availability of commercial UAVs has allowed explosive components to be incorporated with ease.

Drone-dropped munitions can include adapted military ordnance such as grenades, mortar rounds, submunitions from cluster munitions and mines. When IEDs are used as drone munitions, they typically consist of a small military explosive charge encased in a fragmentation sleeve and are equipped with an impact fuze – either electrical or mechanical – designed to detonate upon impact with a target or the ground. In some cases, the fuzing mechanisms of standard military munitions are altered to enable deployment by UAVs. These modifications often involve disabling built-in safety and arming features, which can significantly increase the sensitivity and risk posed by the munition.

A recent development has been the introduction of weaponised UAVs into conflict zones such as Mali, Libya and Sudan

First-person-view (FPV) drones are typically single-use weapons that can be employed against armoured vehicles, supply trucks, defensive positions, such as trenches and bunkers, or groups of personnel in open areas. They are commonly equipped with underslung shaped-charge warheads, often repurposed from rocket-propelled grenades or decommissioned anti-tank missiles. Detonation is usually triggered by a makeshift electrical switch mounted on the nose of the warhead. First-person-view drones that fail to detonate may remain highly sensitive, so their safe handling should involve selective disruption techniques similar to those used in IED disposal.

Explosions at ammunition storage areas

Accidental explosions at ASAs or unplanned explosions at munition sites (UEMS) as they are also known have been a major cause of casualties in Africa. From 1979–2024, over 31 000 casualties were recorded in more than 674 incidents worldwide.¹⁹ Accidental explosions at ASAs occur for various reasons, including improper storage and handling, poor record keeping and accounting, unsafe ammunition storage and management, and a lack of appropriately trained personnel to conduct basic ammunition management tasks.

In Africa, the proximity of ASAs to civilian homes has made accidental explosions particularly catastrophic. Some of the worst incidents are shown in Chart 4.²⁰

Chart 4: Significant incidents in Africa involving unplanned explosions at munitions sites

Date	Location	Casualties
21 December 1987	Alexandria, Egypt	1 006
27 January 2002	Lagos, Nigeria	6 500
29 April 2009	Dar es Salaam, Tanzania	726
4 March 2012	Brazzaville, Republic of Congo	3 777
7 March 2022	Bata, Equatorial Guinea	705

The impact of the accidental explosion at a military ASA in Bata, Equatorial Guinea, on 7 March 2021, is shown in the photograph below.

Chart 5: Effects of the Bata ASA explosion



Image credit: José Luis Abecia, EPA

It is not just peacetime accidents that can lead to catastrophic explosions at ASAs. During armed conflict, ASAs are often regarded as strategically important targets and are afforded a high priority for attack, particularly with long-range air-delivered weapons. Such attacks can cause large explosions at the ASA being targeted and can also lead to the spread of substantial quantities of unexploded ordnance (UXO) over large areas. Chart 6 shows the results of an attack with air-delivered weapons on an explosive store house at a Libyan ASA. While some of the UXO has mass exploded, a sizeable proportion of the explosive store house contents have not exploded and have been liberally spread across the area.

Chart 6: Explosive store house destroyed by NATO air attack, Libya, 2011



Image credit: Paul Grimsley

The primary consequence of both accidental and deliberate explosions at ASAs is that explosive ordnance can be spread over very wide areas. If the ASA is located close to homes, this can result in substantial casualties. The explosive ordnance ejected during the blast can arm in flight and detonate upon impact even at considerable distances from the explosion's epicentre.

The metallic content of ERW can attract attention. Children might be curious and tempted to collect small items of ejected ordnance with devastating consequences

Another impact is that the metallic content of ERW can attract the attention of those interested in its scrap metal value. Children might be curious and tempted to collect small items of ejected ordnance with devastating consequences. The explosive content of ERW is also of interest to NSAGs. In Libya, unexploded artillery shells containing high explosives have been repurposed for use in vehicle-borne improvised IEDs. The image below shows a large suicide vehicle-borne IED intercepted by Libyan authorities en route to its target. The main charge was constructed using artillery shells filled with high explosives.

Chart 7: Libya vehicle-borne IED, January 2018



Image credit: Libyan Ministry of the Interior

Explosions at ASAs pose significant challenges for the authorities in responding to these incidents as dangerous ERW, at very high densities, may be spread over considerable areas. The photograph below highlights the level of contamination that may exist at an ASA following an explosion.

Chart 8: Contamination from an explosion at an ASA



Image credit: Paul Grimsley

Chapter 3

Legal and normative frameworks

International humanitarian law (IHL), the CCW Amended Protocol II (1996) and Protocol V (2003), the APMBC, and the CCM are the legal pillars of HMA that drive a comprehensive and integrated response against explosive ordnance. To implement these instruments, the IMAS and NMAS were developed. While the legal instruments set out binding rules – such as prohibitions on the use of anti-personnel landmines, requirements for clearance of contaminated areas, victim assistance and risk education – the IMAS provides detailed technical guidance and standardised procedures to implement these obligations effectively and safely in the field.

International conventions

International humanitarian law

IHL, especially as codified in the Geneva Conventions and their Additional Protocols and customary rules of IHL, sets out key rules governing the conduct of hostilities and the means and methods of warfare. At its core, it is guided by the principles of distinction, proportionality and precaution. The principle of distinction requires parties to a conflict to distinguish between combatants and civilians and between military objectives and civilian objects. This is particularly relevant to the use of anti-personnel mines, which are incapable of distinguishing between soldiers and civilians. Anti-personnel mines continue to pose a danger long after hostilities have ceased, resulting in civilian casualties and impeding post-conflict recovery.

The principle of proportionality prohibits attacks in which the expected incidental loss of civilian life or injury or damage to civilian objects would be excessive in relation to the concrete and direct military advantage anticipated. In the context of landmines and cluster munitions, this means that their deployment must be carefully evaluated: the long-term risks posed to civilians must not outweigh the short-term tactical benefits. For example, placing mines near civilian infrastructure or agricultural areas may be considered disproportionate if the military advantage is minimal compared to the foreseeable harm to civilian lives and livelihoods.

IHL also requires parties to take all feasible precautions to minimise harm to civilians, including warning affected populations, marking and fencing hazardous

areas and recording mine locations for eventual clearance. These legal obligations collectively seek to limit the enduring humanitarian consequences of mines, cluster munitions and ERW and ensure accountability for their use during armed conflict.

Convention on Certain Conventional Weapons

The CCW, formally known as the Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons Which May Be Deemed to Be Excessively Injurious or to Have Indiscriminate Effects, was adopted in 1980 and entered into force in 1983. The CCW seeks to restrict or prohibit the use of specific types of conventional weapons that are considered to cause unnecessary suffering to combatants or have indiscriminate effects on civilians. It provides a legal framework aimed at balancing military necessity with humanitarian considerations, forming a key part of IHL.

The Anti-Personnel Mine Ban Convention, adopted on 18 September 1997, was a critical milestone in the world's collective action against landmines

The CCW is structured as a framework convention with a set of annexed protocols, each addressing a different category of weapon or method of warfare. The most relevant protocols include:

- Protocol II regulates the use of landmines, booby traps and other devices, setting standards for detectability, record keeping and protections for civilians.
- Protocol V focuses specifically on ERW, requiring parties to clear UXO, share information and take measures to protect civilians after hostilities end.
- Other protocols cover weapons such as incendiary devices, weapons with non-detectable fragments and blinding laser weapons.

To be full state parties to the CCW, states must agree to be bounded by at least two of its five Protocols. To date, 17 African states are High Contracting Parties, having committed to both Protocol II (original or amended) and Protocol V. Eight African states have committed to one of these two key Protocols while three have signed but not yet acceded to the Convention.²¹

Anti-Personnel Mine Ban Convention

The APMBC was a critical milestone in the world's collective action against landmines. It was adopted in Oslo, Norway, on 18 September 1997 and came into force in 1999.²² It stems from a long advocacy process led by an umbrella

of civil society organisations gathered within the International Campaign to Ban Landmines and the ICRC. Civil society advocacy was primarily supported by a group of like-minded states. The initiative aimed to raise broader awareness about the dire consequences of landmines on human security and drive a collective, robust response.

The culmination of the five-year advocacy from 1992–1997 was the APMBC, a legally binding framework aiming to end anti-personnel mine-related atrocities. Its main provisions are as follows:²³

- Article 1 – General obligations
 - States must never use, produce, stockpile or transfer anti-personnel mines.
 - They must also not help or encourage anyone to do so.
- Article 4 – Destruction of stockpiles
 - States must destroy all stockpiled anti-personnel mines within four years of joining the treaty.
 - A small number may be kept for training or research purposes.
- Article 5 – Clearance of mined areas
 - States must clear all mined areas under their control within 10 years.
 - Dangerous areas must be marked, fenced and monitored until cleared.
- Article 6 – International cooperation and assistance
 - States can request or provide assistance for mine clearance, stockpile destruction, victim assistance and risk education.
- Article 7 – Transparency and reporting
 - States must submit annual reports on progress in clearance and destruction, number of retained mines and help provided or received.

Many state parties have engaged in large-scale demining with substantial support from civil society in the fulfilment of their clearance obligation. Since 1997, the Convention has been the core framework guiding HMA. It has paved the way for large-scale humanitarian demining programmes over the last 27 years.

So far, it has secured membership from 165 countries worldwide. Given its wide acceptance by states, including 34 of the 50 recorded landmine producers, it has significantly contributed to decreasing the use and production of anti-personnel landmines. Only 33 states, including three African, have not adhered to it yet. The status of the APMBC in Africa is shown below.²⁴

The map displays the following status for African countries:

- Ratification (Dark Blue):** Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Cote d'Ivoire, Democratic Republic of Congo, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe.
- Succession (Medium Blue):** Algeria, Mali, Mauritania, Niger, Chad, Nigeria, Cameroon, Equatorial Guinea, Gabon, Congo, DRC, Angola, Namibia, Botswana, Lesotho, South Africa, Mozambique, Zimbabwe, Malawi, Zambia, Tanzania, Kenya, Uganda, Rwanda, Burundi, Ethiopia, Somalia, Djibouti, Eritrea, Sudan, Egypt, Libya, Tunisia, Morocco, Algeria, Mauritius, Madagascar, Seychelles, Comoros, Reunion, Mayotte, French Polynesia, New Caledonia, Wallis and Futuna, French Southern Territories, French Guiana, Guadeloupe, Martinique, Saint Martin, Saint Pierre and Miquelon, French Polynesia, New Caledonia, Wallis and Futuna, French Southern Territories, French Guiana, Guadeloupe, Martinique, Saint Martin, Saint Pierre and Miquelon.
- Non-signatory (Grey):** Mauritania, Mali, Niger, Chad, Nigeria, Cameroon, Equatorial Guinea, Gabon, Congo, DRC, Angola, Namibia, Botswana, Lesotho, South Africa, Mozambique, Zimbabwe, Malawi, Zambia, Tanzania, Kenya, Uganda, Rwanda, Burundi, Ethiopia, Somalia, Djibouti, Eritrea, Sudan, Egypt, Libya, Tunisia, Morocco, Algeria, Mauritius, Madagascar, Seychelles, Comoros, Reunion, Mayotte, French Polynesia, New Caledonia, Wallis and Futuna, French Southern Territories, French Guiana, Guadeloupe, Martinique, Saint Martin, Saint Pierre and Miquelon, French Polynesia, New Caledonia, Wallis and Futuna, French Southern Territories, French Guiana, Guadeloupe, Martinique, Saint Martin, Saint Pierre and Miquelon.

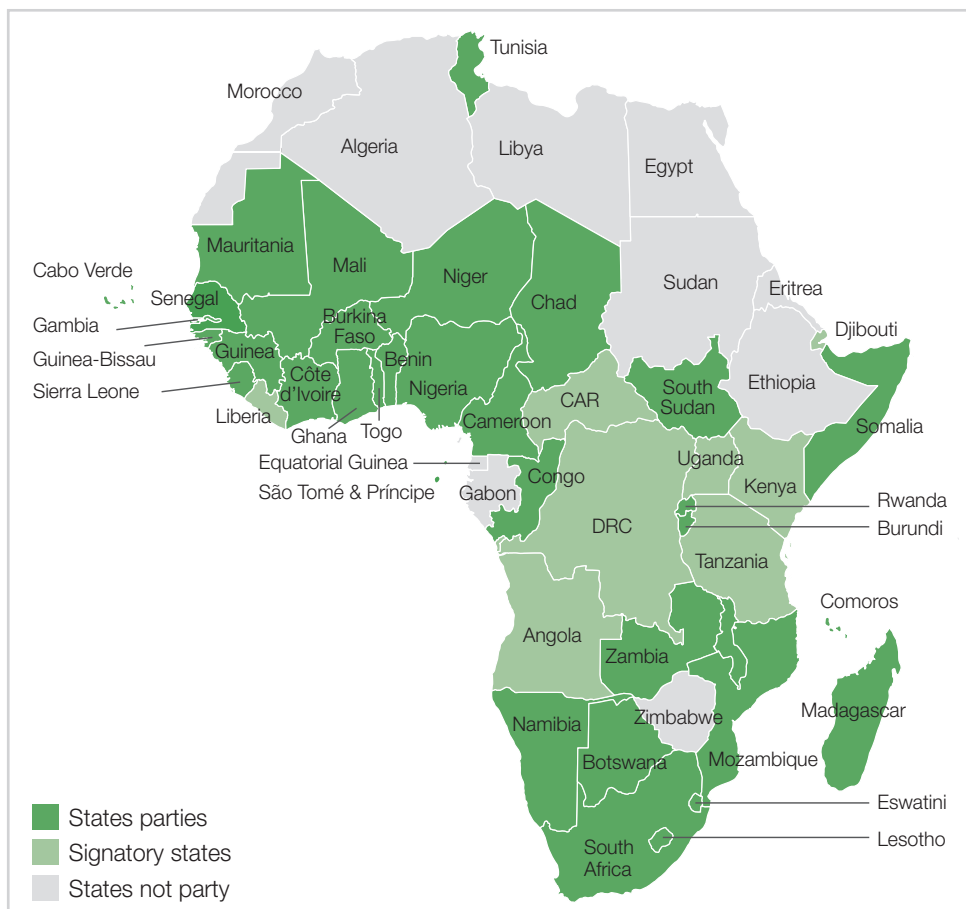
The CCM, adopted on 30 May 2008, emerged against the backdrop of a long debate dating back to the 1960s on the indiscriminate human suffering caused by cluster munitions.²⁵ Efforts to ban cluster munitions remained unsuccessful until the late 2000s. In response to the ongoing harm they cause to civilians, a group of states launched the 'Oslo Process' in 2006, culminating in the Oslo Declaration on Cluster Munitions in February 2007. The CCM was adopted a year later. Its main provisions are as follows:²⁶

- 18

- Article 5 – Victim assistance
 - States must assist cluster munition victims, including medical care, rehabilitation, psychological support and social and economic inclusion.
- Article 6 – International cooperation and assistance
 - States can seek or offer support for clearance, victim assistance, stockpile destruction, risk education and capacity building.
- Article 7 – Transparency measures
 - States must submit annual reports on stockpile status, clearance progress, victim assistance activities and retained munitions, if any.

Like the APMBC, the adoption of the CCM was characterised by a vital synergy between civil society organisations, states and international organisations. Another critical element that prompted the swift adoption of the CCM after Oslo 2007 was cluster munition victims' continuous and vocal participation in the adoption process. The status of the CCM in Africa is shown in Chart 10.²⁷

Chart 10: Status of the CCM in Africa as of February 2025



Mine action standards

International Mine Action Standards

The IMAS and the NMAS, which implement IMAS at the country level, are the primary standards governing HMA.

Since their issuance by the United Nations Mine Action Service (UNMAS) in 1997, the original International Standards for Humanitarian Mine Clearance Operations have evolved. In 2001, they were revised and renamed the IMAS. This change responded to the need to expand the standards' scope and to reflect evolving operational practices, procedures and norms. Consequently, the IMAS has developed as an agile set of documents, open to continuous amendment and improvement about every three years.

IMAS exist to ensure that mine action activities – including survey, clearance, explosive ordnance disposal, risk education and victim assistance – are carried out safely, effectively and in accordance with IHL and best practices. They provide a common framework for national authorities, demining operators and donors, promoting consistency, accountability and quality across mine action programmes throughout the world. Their purpose is to minimise risks to affected populations and field personnel, enhance operational efficiency and support the fulfilment of legal obligations.

Given the United Nations' (UN) responsibility for developing and maintaining international mine standards, UNMAS, its mine action service, has been designated as guarantor of the IMAS framework, which includes the IMAS themselves, Technical Notes for Mine Action and Test and Evaluation Protocols. To perform its mandate, UNMAS has secured the technical help of the Geneva International Centre for Humanitarian Demining to produce and update the IMAS. Through that partnership, an IMAS Review Board –bringing together affected and donor states, non-governmental organisations (NGOs), UN agencies, demining companies, demining schools, military and independent experts, and others – is mobilised to prepare, review and revise the IMAS.

National Mine Action Standards

NMAS are developed in line with IMAS. As country-specific regulations and guidelines governing mine action activities, NMAS reflect IMAS tailoring to respond to local challenges. The national standards are developed by national authorities in charge of mine action, occasionally with technical support from UNMAS and other specialised international organisations.

NMAS regulate activities and provide operational details related to all areas of operation of mine action and provide guidelines to ensure the protection and safety of deminers, local populations and the environment. A critical part of NMAS covers

how organisations, teams and individuals are accredited for HMA operations. It also covers country-specific requirements such as the control of explosives on sites subject to clearance. They are designed to foster efficiency and effectiveness by establishing a baseline that harmonises operators' methodologies and approaches to mine action at the national level.

Similarly, they help national mine authorities coordinate actions and monitor progress. NMAS sets training standards for staff of national mine action structures and ensures consistency between national mine action and IMAS. This alignment enables states to meet the expectations of international donors and stakeholders. To maintain this consistency, NMAS is regularly updated to reflect international norms and operational practices.

African frameworks

As one of the most affected continents, Africa has seen strong engagement from its countries in responding to the hazards posed by landmines and ERW. This is evident in the widespread accession to the APMBC and the development of regional frameworks. Africa's home-grown frameworks have all been developed at the AU level and include the 2004 CAPL and the AU PCRD Policy.

The two frameworks (CAPL and PCRD) express Africa's support and commitment to global efforts against explosive contamination. Recognising the urgent need to tackle the threat of landmines and ERW on African soil and worldwide, legal experts at the AU headquarters in Addis Ababa affirm that the frameworks not only complement the APMBC and other key international frameworks but also offer moral and legal ground for HMA in Africa.

Common African Position on Anti-Personnel Landmines

The 2004 Common African Position on Anti-Personnel Landmines was adopted by the AU to reaffirm and strengthen the continent's collective commitment to the APMBC.²⁸ It was coordinated in the age-old African practice of addressing continental and international affairs with consensus and a shared vision. This position emphasised Africa's shared humanitarian concerns about the devastating impact of landmines on civilians, development and post-conflict recovery across the continent.

While the CAPL remains declarative with no legally binding power, it reflects AU member states' collective stance on responding to landmines on the continent and promotes:

- Universalisation of the APMBC encouraging all states to join
- Timely clearance, marking, risk education and victim assistance programmes
- Cooperation and assistance at inter-African and international levels

- Integration of mine action into peacebuilding and development strategies
- African leadership in global mine action and strong treaty adherence

African Union Post-Conflict Reconstruction and Development Policy

The AU PCRDR Policy, adopted in 2006, provides a comprehensive framework to guide African states and partners in addressing the root causes and consequences of conflict.²⁹ It is designed to support countries emerging from conflict in achieving sustainable peace, recovery and development, aligned with the AU's broader peace and security agenda.

The policy is guided by five key principles: African leadership; national and local ownership; inclusiveness, equity and non-discrimination; cooperation and coherence; and capacity-building for sustainability and structured around the six key pillars below.

- Security, including disarmament, demobilisation and reintegration, mine action, and security sector reform
- Humanitarian assistance, addressing the needs of displaced people, refugees and vulnerable populations
- Political governance and transition, supporting legitimate, inclusive political processes and rebuilding institutions
- Socio-economic reconstruction and development, restoring basic services, infrastructure and livelihoods
- Human rights, justice and reconciliation, promoting transitional justice, rule of law and healing processes
- Women and youth, ensuring their participation and addressing their specific post-conflict needs

Through the policy, AU member states have placed mine action among Africa's PCRDR central elements, which they believe is a critical step in enhancing human security, preventing landmine and ERW casualties and fostering the resumption of economic activities sustaining livelihoods in the long run.

The policy provides a framework for the rapid and effective implementation of reconstruction activities. Furthermore, it encourages member states to engage in land release through landmine detection and clearance activities. These activities have ripple effects, including reigniting economic activity, promoting access to arable lands to support food security, enhancing the mobility of people and goods, facilitating the return and resettlement of displaced people and enabling the delivery of humanitarian assistance.

Chapter 4

Existing approaches in detection and disposal

The conventional approach in HMA programmes begins with a non-technical survey (NTS) to assess the boundaries of areas affected by explosive hazards. This process helps to delimit the suspected hazardous area. Thereafter, clearance operations may be conducted using either manual or mechanical methods. The complexity of the clearance operation is affected greatly by the level of vegetation and the nature of the terrain. The entire process must be conducted in a systematic and methodical manner with close attention paid to quality assurance. The final step in the clearance operation is land release in which the cleared area is confirmed to be free of explosive hazards and can be returned to productive economic use.

Manual detection

A core element of HMA is manual mine clearance, with many of the skills and techniques derived from those developed by armed forces. A seminal Geneva International Centre for Humanitarian Demining report on manual mine clearance came to the following conclusions:

Manual mine clearance equipment and techniques have evolved over the years by adapting what were basically military skills to the needs of a specialist, largely civilian, activity. But manual clearance is still perceived as slow, repetitive, potentially dangerous and overly expensive, and opinions differ widely on the best ways to conduct clearance operations.³⁰

The report also concluded that the average clearance rate is about 15–20 square metres per deminer per day, a figure that is heavily influenced by the type of vegetation and the level of metallic contamination in the ground.

Over the last 30 years, metal detectors have been central to demining operations, especially for locating buried mines and ERW. Several factors have contributed to their growing use in the sector. Handheld metal detectors are cost-effective and efficient – but only when operated by fully trained and supervised personnel. However, their effectiveness is limited when detecting mines and IEDs with low or no metal content. Performance on the ground is also variable and is affected

by various factors including soil permittivity, water content and the presence of extraneous metallic contamination.

Recent advances in handheld detectors have integrated miniature GPR systems alongside traditional metal detection technology. All handheld detectors share the same limitations: they require highly trained operators who must work in close proximity to explosive hazards, where even a momentary lapse of concentration can have catastrophic consequences.

Biological detection

Animals, particularly dogs, have been used for explosive detection for many years due to their excellent sense of smell. More recently, high assurance search dogs have proved particularly adept at finding explosive devices that are difficult to locate with handheld electronic devices, such as mines and IEDs with low metal content.

Chart 11: Explosive detection dog conducting high assurance search



Image credit: UNMISS/UNMAS, South Sudan

Mine detection and high assurance search dogs are widely used by HMA NGOs across Africa. One example is APOPO, which operated in the Casamance region of Senegal in cooperation with the NGO, Humanity & Inclusion.³¹ APOPO also used detection rats to locate buried mines and ERW. Chart 12 shows an APOPO rat searching for explosive ordnance in Cambodia.

Chart 12: APOPO detection rat in action



Image credit: APOPO

Mechanical clearance

Not all minefield clearance requires the use of human or animal detection systems to be deployed within hazardous areas. Highly protected and fully armoured platforms may be employed to initiate mines. This approach is particularly suitable in circumstances where low- or zero-metal-content mines have been laid in terrain that makes the use of handheld detectors less effective.

Remotely operated mechanical mine clearance vehicles, with no human operators on-board, are now widely employed in other areas of the world. They are particularly useful for ERW recovery in urban areas damaged through conflict. They are also useful for the mitigation of explosive hazards in ASAs where explosive store houses have been subject to mass explosion and UXO remains within the seat of the explosion, mixed with non-explosive debris.

The principal disadvantages of mechanical clearance methods are their reliance on capital-intensive equipment and the high maintenance costs, as the equipment is inevitably damaged during operational use. Mechanical mine clearance systems must be used with great care in areas where the topsoil is thin and the vegetation is poorly anchored, as is often the case in Africa. In these situations, the use of mechanical systems may weaken the surface to such an extent that the topsoil is washed away completely in the next rainy season.

Chart 13: Mechanical minefield clearance



Image credit: Aardvark Group and UNMAS, Libya

Disposal

The disposal of identified explosive hazards usually involves rendering the explosive content of the ordnance safe. Some items of explosive ordnance may be deemed too hazardous to move and must be destroyed on site, often through the application of an explosive donor charge, which is detonated from a safe distance. Certain items of explosive ordnance may be neutralised at the location and then moved to a controlled demolition site for subsequent disposal by detonation.

IEDs can be fabricated from commonly available materials and can employ military explosive ordnance or homemade explosives as the main charge

The routine disposal of explosive items traditionally requires substantial stocks of serviceable explosives, detonators and detonating cord. In many areas in Africa, this poses significant logistical difficulties as explosives are expensive, scarce and hazardous materials to transport. Chart 14 below shows a multi-item demolition prepared for initiation in Africa. In this case, the serviceable explosives employed have been acquired from the mining industry. In conflict-affected environments, serviceable explosives are also attractive to NSAGs as they can easily be incorporated into the main charge of IEDs.

The versatility and ubiquity of IEDs present their own challenges. IEDs can be fabricated from commonly available materials and can employ military explosive

ordnance or homemade explosives as the main charge. They can be employed in large numbers and include anti-handling circuits designed to increase the difficulty of rendering the device safe. Some countries have IED disposal units that employ sophisticated robotic deployed weapon systems to deal with the IED threat remotely. Such systems though are very expensive and require logistical and equipment support capabilities that are generally not available in Africa.

Chart 14: Multi-item demolition of recovered ammunition



Image credit: Graham Brooks

Chapter 5

Technological advances in detection and disposal

Since the introduction of the APMBC, there have been significant advances in detection and clearance technologies, alongside major improvements in computer processing capabilities that enable sophisticated automated image and video analysis. This section will look at key technologies that have been or are in the process of being developed, linking UAVs, remote sensing and data processing.

Remote sensing technologies

Technological advances in remote sensing technologies have traditionally been driven by military applications. Recent advances in sensor technology and substantial reductions in cost have seen remote sensing become much more widely used in the commercial and humanitarian domains.

Camera systems

Visible light electro-optical systems, or camera systems as they are more commonly known, encompass imaging systems that operate in the visible light spectrum. The pace of technological change since the 1970s, when the first digital imaging systems were introduced, has been rapid. While military applications initially drove research and development, in the past two decades, the commercial sector has set the pace. The following technological developments have resulted in the availability of highly versatile camera systems capable of taking very high-resolution still images and video footage:

- Camera sensors have improved resolution by increasing pixel count and reducing pixel pitch.
- Low-light capabilities have improved through the increased dynamic range of image capture sensors.
- Camera-level image stabilisation techniques have been introduced to reduce image blur, particularly important for sensors on moving or vibrating platforms such as UAVs.

- Computing power and algorithms have increased to support image compression at the sensor or camera level.
- High-capacity solid-state digital storage systems have been introduced.
- Sensor electronics now allow data to be written to non-volatile storage at very high speeds and in real time.

UAV-mounted camera systems have been widely evaluated and shown significant merits in HMA applications (see Chart 15). The principal advantages of UAV-mounted imaging systems are that they can cover large areas with great efficiency. The technology is sustainable, especially when paired with renewable autonomous power sources such as solar panels and micro wind turbines.

Remote sensing removes the need for operators to be exposed to danger, which is particularly important when the outer boundaries of suspected hazardous areas and confirmed hazardous areas are being identified. They can also provide digital imagery products capable of analysis using automated AI tools. The HMA sector is leveraging on developments that have been proven in other commercial sectors. Finally, it is now a cost-effective technology, and both deployment systems (UAVs and sensors) are relatively affordable.

Chart 15: Electro-optical system on a UAV for mine and ERW detection



Image credit: M Jebsen, ICRC

There are no technological barriers to using UAV-mounted camera systems for mine action in Africa; in fact, such systems have already been trialled on the continent. This technology is widely used in the mining and the upstream oil and gas sectors. However, several issues may need to be addressed, including:

- Environmental considerations: Like the human eye, camera systems cannot penetrate vegetation, smoke and precipitation. They are thus better suited to arid and semi-arid areas with minimal ground cover.

- Legal constraints: Some countries may also have issue with the security implications of imagery collection, particularly in sensitive areas such as border regions, conflict zones and close to military installations.
- Data processing: High-resolution camera systems, even when employed with image compression algorithms, generate massive quantities of data and this mandates the use of some form of automated data processing system. A human operator alone, with no automated assistance, would be incapable of drawing meaningful conclusions from the large quantity of data collected from even short UAV operations. Apart from identifying the largest, surface-laid ERW, it is virtually impossible for a human operator to detect explosive ordnance in real time.

Thermal imaging

Thermal imaging, or infrared thermography, detects electromagnetic radiation within the infrared spectrum. Thermal imaging is a technique that allows infrared energy, which is not in the visible light spectrum, to be detected and displayed. The basis for the technology is that all objects emit radiation according to their surface temperature. The original research and development of thermal imaging technology was driven by military applications but reductions in sensor cost and significant improvements in sensor resolution have enabled a massive growth in commercial and consumer thermal imaging systems. Chart 16 below provides an example of thermal imaging output from a commercial sensor taken in absolute darkness; the object viewed is an adult African rhinoceros.

Chart 16: Thermal imaging sensor product

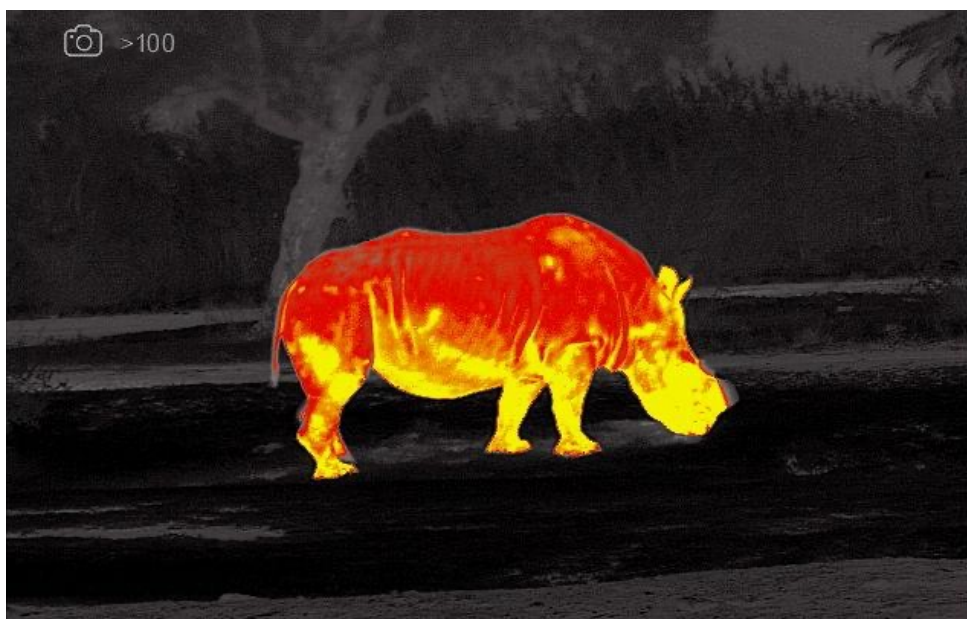


Image credit: Bob Seddon

The key technical characteristics and resolution of thermal imaging sensors are defined by the number of pixels and the pixel pitch. Commercial thermal imaging sensors i.e. those not subject to wide-ranging military technology export controls, typically have a resolution of between 240 x 240 pixels and 1 024 x 768 pixels and a pixel pitch of between 12 μm and 17 μm .

One of the key factors to consider with thermal imaging sensors is that even the best sensors provide an image resolution, in terms of pixel count, which is substantially less than can be achieved with camera systems operating in the visible light band. This has significant implications on the height above ground at which thermal sensors can operate and the utility of image processing systems for evaluating thermal images.

Early thermal imaging systems were large and cumbersome and often required additional cooling equipment. The thermal imaging sensor at the heart of many modern commercial thermal imaging systems is the size of a fingernail and operates at ambient temperature. Chart 17 shows thermal imaging sensors that are employed in hand-held commercial thermal imaging products.

Chart 17: Commercial thermal imaging sensors

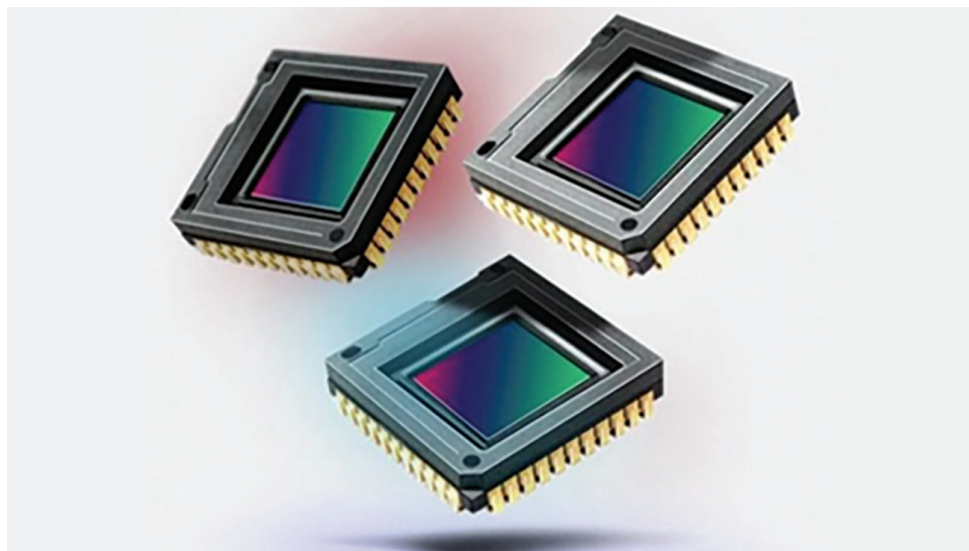


Image credit: Pulsar

The application of thermal imaging sensors has been the subject of research spanning several decades. Recently, a comprehensive review of the technology was conducted by several eminent stakeholders and researchers in the field of HMA.³² Thermal imaging technology has improved, and the ever-increasing miniaturisation of electronic and optical components has led to compact systems that may be deployed by small UAVs. There are now a wide variety of commercially

available UAVs that offer integrated thermal imaging sensors. One such example is shown in Chart 18.³³

The Odyssey 2025 Project³⁴ by Humanity & Inclusion provided field validation of the viability of collecting airborne thermal imaging data on landmines. This fieldwork was conducted in the Sahara Desert in northern Chad and demonstrated the usefulness of the technology in detecting both anti-personnel and anti-vehicle mines.³⁵ It concluded:

We can now confirm we are able to locate mines buried in the desert using drones equipped with infrared cameras. It is quite remarkable! It now takes us minutes – rather than sometimes weeks using conventional methods – to collect visual information of a hazardous area and search for signs of explosive devices. A sound grasp of these new methods will accelerate demining operations and ultimately land release for local populations.³⁶

Chart 18: Skydio UAV with integrated Teledyne FLIR thermal imaging system



Image credit: Skydio

A key issue in applying thermal imaging sensors to the HMA domain is that by increasing the probability of detection of explosive ordnance, the false alarm rate is also likely to increase, with subsequent impacts on user confidence.³⁷

It is apparent that commercial thermal imaging systems have come of age, and there are a wide variety of systems available that have been integrated with UAVs. The key practical considerations for applying thermal imaging systems include the following:

- Environmental: Thermal imaging systems are limited by dense vegetation and perform poorly in heavy precipitation, though they can penetrate some dust and smoke.

- Availability of deployment platforms: To be used flexibly, thermal imaging systems are best mounted on UAVs. A poorer alternative is to mount them on extendable masts attached to vehicles.
- Infrastructure: Modern thermal imaging systems are robust but need reliable power for charging UAV and sensor batteries. Autonomous power sources are essential in low-capacity and conflict-affected areas.
- Cost: Although prices have decreased in recent years, thermal imaging systems and UAVs are still relatively expensive compared to conventional camera systems. Their use in harsh environments requires sufficient spares to manage the inevitable wear and tear during operations.
- Data processing: Thermal imaging generates large data volumes beyond human capacity making robust post-processing systems essential.

Light detection and ranging

LiDAR is a remote sensing technology. LiDAR systems emit pulses that reflect off objects and surfaces, measuring the time it takes for the pulse to return to the sensor. This time of flight is essential for calculating distance from the sensor to the object. By scanning the target area with the laser, LiDAR systems can create a dense 3D point cloud, which is a collection of points representing the shape and features of the environment. The basic components of LiDAR system are shown below.³⁸ A LiDAR sensor typically contains a laser, a scanner and a highly accurate global navigation satellite system (GNSS).

Chart 19: LiDAR system components

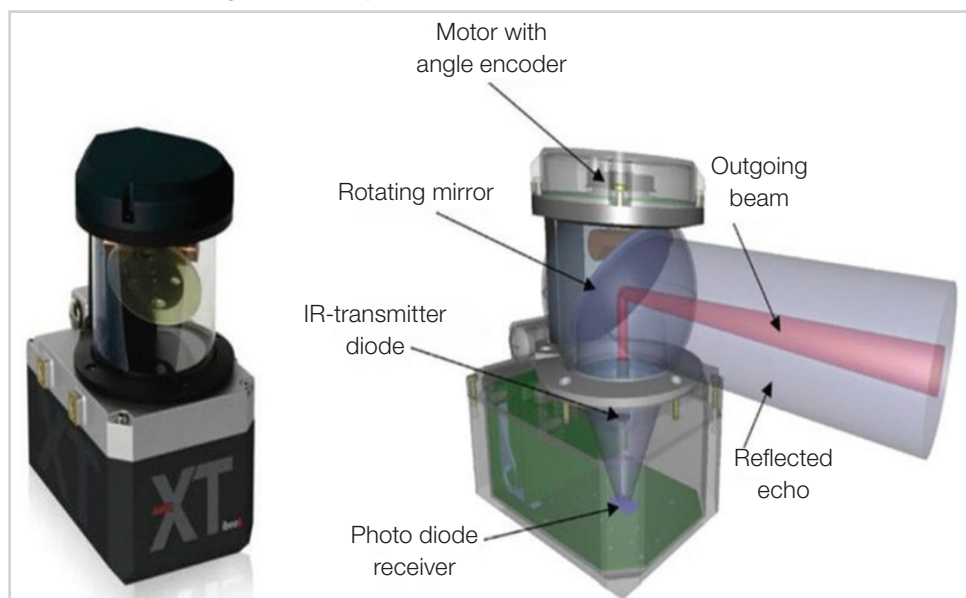


Image credit: Elprocus

As with other types of sensors, LiDAR can be used during NTS and TS to identify locations contaminated with explosive hazards. While LiDAR sensors may be mounted on tripods and extendable masts fixed to vehicles, the most versatile means of deployment is by using airborne platforms, such as UAVs. Chart 20 shows a Rousescene LiDAR system mounted on a commercial UAV during an operational trial conducted by The HALO Trust.

Chart 20: Rousescene LiDARPod mounted on a DJI M600 Pro, Angola



Image credit: Claire Lovelace

The principal advantage of LiDAR over visible light electro-optical systems is its ability to penetrate dense vegetation. This makes it especially effective in tropical rainforests and during rainy seasons when savannah grass is thick, enabling ground imaging beyond the reach of most other remote sensing technologies.

The key practical considerations for applying LiDAR systems in HMA applications are:

- **Safety:** LiDAR systems must comply with national safety laws and may require licensing. Most are Class 1 (safe under normal use) or Class 1M (safe except when viewed with magnifying optics).
- **Positional accuracy:** To have the greatest utility, LiDAR data must be precisely geo-referenced, which often requires enhanced techniques like differential GNSS, as standard UAV GNSS systems lack sufficient accuracy.
- **Cost:** LiDAR sensors are larger and more expensive than visible light and thermal imaging sensors, and require bigger UAVs for deployment.
- **Data processing:** LiDAR generates huge quantities of data requiring complex post-processing, making it more suitable for planned minefield and ERW clearance operations than ASA responses.

Synthetic aperture radar

SAR is an active imaging technique that uses radio frequency pulses emitted by its own radar antenna to capture high-resolution images of surfaces. SAR is an active imaging technique i.e. it emits its own radar signals and analyses the reflected echo from the ground or a target. SAR combines the motion of the radar antenna with sophisticated data processing to provide an image resolution which is higher than conventional radar alone.

SAR technology is reducing in size and may now be integrated into medium-sized UAVs. The principal advantage of SAR imaging over other conventional imaging technologies is that it is not degraded by adverse weather, unlike visible light or thermal imaging systems. SAR systems can see through light vegetation and image the ground below, making them a useful option for identifying surface-laid mines and ERW.

The primary advantage of SAR is its ability to deliver high-resolution images with consistent quality regardless of weather conditions. However, it cannot penetrate dense materials to image deeply buried objects. SAR also has a lower level of spatial resolution when compared to other remote sensing techniques i.e. the image quality obtained lacks the fidelity of camera, thermal imaging and LiDAR systems.

SAR technology has largely been developed in the military domain and was originally deployed on large, fixed-wing air platforms and satellites. As technological advances have been made, SAR systems have been deployed on larger UAVs. The photograph below shows a Lynx fine-resolution real-time SAR system mounted on a General Atomics I-Gnat UAV. The SAR system payload weighs 50 kg.

Chart 21: Lynx SAR mounted on a General Atomics I-Gnat UAV



Image credit: Sandia National Laboratory

The performance of the SAR system is dependent on the height at which it is operated. When operated at medium to low altitude, a UAV-mounted SAR system can detect objects that have been buried in roads and tracks or placed adjacent to routes. There is obviously utility here for the detection of IEDs, especially when used with coherent change detection (CCD) methods employed over multiple flights, for those organisations that can afford to operate this type of UAV.

SAR systems, especially when mounted on long-endurance UAVs, are capable of scanning very wide areas or long routes. This makes airborne SAR systems potentially suitable for route-proving operations, enabling the detection of newly placed IEDs or anti-vehicle mines along remote roads and tracks in sparsely populated areas.

Nevertheless, SAR, when considered as a remote sensing technology for use in the HMA sector, is not as technically mature as the other remote sensing technologies considered so far in this monograph. SAR appears to offer several significant benefits for use in the HMA domain:

- It can be carried by UAVs thus allowing the safe, non-intrusive inspection of suspected or confirmed hazardous areas.
- It can detect metallic and non-metallic objects, unlike magnetometers (metal detectors) whose applicability is limited to detecting metal objects.
- It can produce images of buried objects.
- It offers an all-weather capability.

The applicability of SAR to mine action is an active area of research and the combination of relatively small SAR systems and UAVs is starting to deliver promising results.³⁹

While the technology is not yet ripe enough to be deployed globally, the following practical considerations should be taken into account:

- Maturity of technology: SAR is less technically mature for mine action than other remote sensing methods. More field experience across Africa's various terrains is needed before it can be considered a low-risk option.
- Regulatory implications of employing large UAVs: Gaining approval for medium or large UAVs, especially for low-altitude or beyond-visual range flights, is often more difficult than for small UAVs operating under visual flight rules.
- Data processing: SAR systems generate considerable data volumes requiring post-processing. CCD can help identify newly introduced hazards.

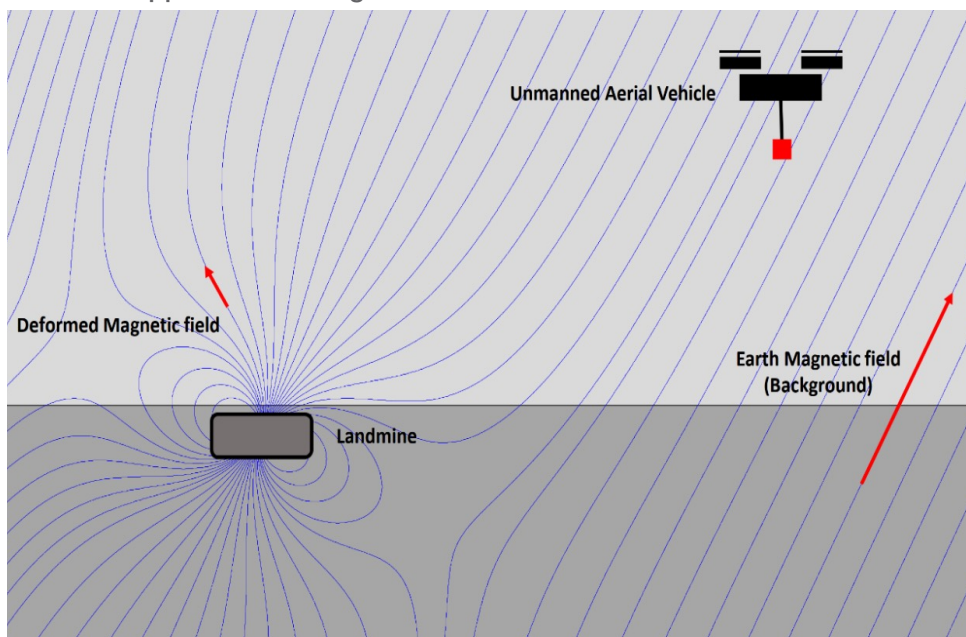
Electromagnetic sensing

Electromagnetic sensing, particularly using electromagnetic induction detectors, plays a crucial role in HMA by non-intrusively detecting buried metal objects. This is the baseline technology underpinning most handheld metal detectors.

Magnetometers measure magnetic fields and can detect distortions in the earth's magnetic field caused by the metal components in most explosive ordnance. The operation of a magnetometer in a landmine detection application is shown in Chart 22 below.⁴⁰ Magnetometers have traditionally been integrated with accurate GNSS mapping and recording systems and have been deployed by person or vehicle.

More recently, magnetometers have been integrated into small UAVs, proving especially useful for surveying hard-to-reach areas, such as swamps, marshes and shallow water zones.

Chart 22: Application of magnetometers to landmine detection



Source: Australian Army Research Centre

Ground-penetrating radar

Alternative approaches to magnetometers include the employment of airborne GPR for explosive ordnance detection. GPR systems offer the significant advantage of detecting explosive ordnance with low or no metal content. They are particularly effective at detecting low-metal pressure plates used in victim-operated IEDs, which are nearly impossible to detect with other electromagnetic sensors. The photograph below shows a RadSys Zond Aero NG GPR used in an HMA application.⁴¹

Chart 23: Airborne GPR on a UAV



Image credit: SPH Engineering

While GPR and magnetometers have their limitations, when data from both types of sensors is combined, significant benefits may be obtained in terms of increasing the probability of detection and reducing the false alarm rate.

Remote sensing technology in Africa

Remote sensing technology is not new to Africa and has been applied across various fields, including:

- Agriculture and food security: The Famine Early Warning Systems Network uses satellite imagery to track rainfall, vegetation and soil moisture across the Sahel, Horn of Africa and Southern Africa helping governments anticipate drought and food insecurity.
- Environmental monitoring and conservation: South Africa's National Space Agency uses remote sensing data to monitor land degradation and biodiversity loss in protected areas such as the Kruger National Park.
- Disaster management: Malawi has used drones and satellite data to map flood-prone areas, improving disaster preparedness and enabling the government to relocate vulnerable communities.
- Urban planning: In Nigeria, the Humanitarian Data Exchange partners use high-resolution satellite imagery to map displacement and improve aid delivery and infrastructure planning.
- Natural resource and wildlife monitoring: Zambia uses satellite data to manage and monitor mining operations, checking compliance with environmental standards and detecting unlicensed activities.

Remote sensing has also been used in HMA efforts in Africa through two key projects. The Odyssey 2025 Project⁴² was extensively tested in Chad and concluded that:

Airborne infrared thermography can be used to locate buried landmines from small drones in Sahara Desert minefields. We found that the strength of thermal anomalies can vary by day, indicating that generalizations cannot be made without more field data to substantiate claims. Ideally, this would be undertaken across many arid and semi-arid locations in different countries contaminated with landmines.

The project found that using thermal imaging alone is not a panacea for landmine detection, but combining it with other sensors can improve overall effectiveness.

‘Remote sensing is not a replacement for, but is
complimentary to, conventional minefield
non-technical survey’

The HALO Trust conducted a research project using LiDAR technology in Angola. The system provided solid evidence to help focus minefield clearance operations⁴³ and concluded the following:

This research has proven that UAV-mounted LiDAR systems can be used to detect minefield features which can be indicators of minelaying. The LiDAR data provided evidence of trenches, craters, and foxholes across all tasks surveyed, which were either undetectable or only partially visible in satellite imagery. Remote sensing is not a replacement for, but is complimentary to, conventional minefield non-technical survey. This work demonstrates how valuable LiDAR data can be to provide evidence that is not obtainable by other means, offering advantages over RGB [Red, Green, Blue] and TIR [Thermal Infrared] imagery when looking for minefield features hidden by vegetation.

Therefore, nothing specific prevents the further deployment of remote sensing technology in HMA across Africa. As elsewhere in the world, the following considerations must be taken into account depending on the context:

- Environmental considerations: Weapon contamination in Africa spans diverse terrains including jungles, deserts, arid fields and urban areas. Technologies must be carefully chosen and tested to suit each environment.

- **Legislation:** Laws, regulations and policy regarding remote sensing vary across Africa; national legislation must be considered when planning projects.
- **Availability of equipment and repairs:** Not all equipment is readily available across Africa. Importing adds complexity, including licensing, sanctions and repair challenges.
- **Cost:** Funding for survey and clearance projects varies across Africa. Equipment costs must be carefully considered to ensure sustainability.

Information processing

All sensors generate data. Most modern camera systems employ digital technology, although older analogue systems are still widely used in security applications. Digital camera systems, thermal imaging systems, LiDAR and SAR systems generate either static images or, more often, a digital video stream. The information content of the data stream is determined by the resolution i.e. the number of pixels in a single image, the number of colours in the image and the frame rate of the image stream i.e. the number of images per second.

In broad terms, the higher the pixel count, the greater the number of colours present in the image and the higher the frame rate, the greater the raw data rate generated by the sensor. Image compression, enabled by computer processing in the sensor hardware, can be used to generate an actual video data rate significantly less than the raw data rate. However, excessive video compression can reduce quality and limit the effectiveness of automated image processing tools.

Data deluge

The previous sections of this report have identified candidate remote sensing technologies that could potentially support HMA operations. One of the key issues in using remote airborne sensors for explosive clearance is managing information overload. All sensor types generate large data streams and the higher the resolution, the greater the challenge.

To understand the practical implications of the data deluge problem, it is necessary to understand the actual quantities of data being generated by sensors. The table below provides an overview of the raw video data rates, without embedded compression, for various visible light camera systems and thermal imaging sensors.

Even a cursory examination of the data rates highlights the size of the problem for real world HMA applications. The miniaturisation of solid-state non-volatile memory allows data to be stored on small cards within the sensor system and downloaded after each UAV mission. This data must then be stored and processed, requiring high-capacity (multi-terabyte) processing systems.

Chart 24: Data rate for visible light electro-optical and thermal imaging sensors

Sensor type	Nominal resolution	Frame rate (Hz-per/sec)	Colours/ gradations	Raw data rate
Visible light electro-optical sensors				
TrakkaCam TC-300	1 920 x 1 080 pixels	30 Hz	24 bits (1.6 million)	186.6 MB/sec 11.2 GB/min
Trillium HD 25	1 280 x 720 pixels	30 Hz	24 bits (1.6 million)	82.9 MB/sec 4.9 GB/min
Thermal imaging sensors				
InfRec Thermo FLEX F50	240 x 240 pixels	7.5 Hz	16 bits (65 000)	864 KB/sec 51.8 MB/min
FLIR T530	320 x 240 pixels	30 Hz	16 bits (65 000)	4.6 MB/sec 276 MB/min
FLIR T865	640 x 480 pixels	30 Hz	16 bits (65 000)	18.4 MB/sec 1.1 GB/min

The high-resolution camera systems, operating in raw data form (i.e. without image compression) can generate over 11 gigabytes of data per minute. For a typical 30-minute remote sensing UAV mission, this results in the collection of over 300 GB of data.⁴⁴ Clearly, analysis of this quantity of imagery data mandates the use of some form of automated image processing system.

Deep learning

Deep learning is a type of machine learning that uses AI, usually based on neural networks, to learn from data. Artificial neural networks are informed by the human brain, and they have been used to analyse a wide variety of image types. For example, they have delivered significant benefits in medical imaging analysis, where deep learning algorithms have proven effective in helping human operators identify cancer tumours.

The volume of imagery data generated by remote sensing systems makes it impossible for human operators to reliably process all the visual data. Substantial research in the HMA sector using deep learning technology has shown that object detection algorithms can perform this task reliably.⁴⁵

An object detection algorithm is a set of computer rules to identify and locate specific objects of interest in an image or video. A comprehensive review of object detection algorithms is beyond the scope of this monograph. However, it is worth noting that they are the focus of extensive research, supporting applications from driverless cars to medical imaging diagnostics. A wide variety of proprietary and

open-source algorithms are available. Professor Sawada's team has explored the use of the YOLOv3-Tiny algorithm for detecting mines and ERW. YOLOv3-Tiny, a streamlined version of the YOLOv3 object detection algorithm, works by dividing an image into a grid, predicting bounding boxes and confidence scores for each grid cell, and then using a lighter convolutional neural network (CNN) (Darknet-53) to detect objects efficiently.

Their work was put to the test in a joint project with the ICRC and has shown that deep-learning techniques, when applied to multi-spectral imagery acquired in the HMA domain, can significantly increase the probability of detection while simultaneously reducing the false alarm rate.⁴⁶ The research has reached a level of technical readiness that has attracted interest from commercial entities for further development.

Using deep learning for HMA requires acquiring suitable imagery to train the neural network on. Ideally, high-quality imagery products are required of candidate mines and ERW for this purpose. In a recent trial conducted in a desert environment in Jordan as part of the ICRC–Waseda project, deep-learning techniques combined with imagery from camera systems and thermal sensors detected about 90% of the ERW used in the trial.

At the current state of the art, deep learning – and AI products more broadly – should be considered as complimentary tools in the deployment of remote sensing technologies. In the HMA domain, remote sensing and deep-learning techniques have the most utility in identifying the extent of a suspected hazardous area following an explosion at an ammunition storage site. They also provide an automated detection tool for analysing the imagery collected by remote sensors. Finally, and perhaps most importantly, deep-learning techniques could help HMA stakeholders in reducing the overall size of confirmed hazardous areas, thus allowing scarce resources to be used to best effect.

The performance of deep-learning image detection algorithms will only improve as the underlying neural networks are trained on new data. It is essential, therefore, that HMA stakeholders, particularly those engaged in image collection in operational environments, continue to openly share and exchange imagery on identified mines and ERW.

Coherent change detection

CCD is a technology that detects changes and anomalies between images of the same object at different times. CCD is most often used with SAR imagery, detecting changes by comparing the phase of SAR signals. A loss of phase coherence indicates a change. Originally developed for military intelligence, surveillance and reconnaissance, CCD has been used operationally to detect buried IEDs along routes used by military forces.

The collection of SAR data and the use of CCD techniques is not a low-cost activity and will be beyond the scope of most actors involved in HMA. It does have applicability in circumstances where nations have larger medium-altitude long-endurance UAV platforms capable of mounting SAR sensors. It is also appropriate where there is a significant threat posed by NSAGs employing victim-operated IEDs and mines on routes that are not subject to continuous surveillance by other means. As the cost and weight of SAR systems reduces over time, their usability and usefulness for HMA applications is likely to increase.

Unmanned aerial vehicles

Significant advances have been made over the past decade in both the military and commercial domains in remote sensing, unmanned aerial systems (UASs) and the automated processing of large amounts of sensor acquired data. Similarly, advances in compact, powerful computing have boosted image processing and AI analysis. Small, versatile, commercial UASs are now widely available and capable of carrying substantial sensor payloads.

UAVs are powered aerial vehicles that do not carry a human operator. They form the airborne component of a UAS. The UAS typically includes the launcher, recovery system and ground control or programming units. UAVs may be classified by a wide variety of methods:

- By functional design and wing type
 - Fixed wing
 - Multi-rotor
 - Single rotor
 - Hybrid systems
- By method of operation
 - Remotely piloted (visual range or beyond visual range)
 - Semi-autonomous (pre-programmed prior to launch)
- By flight altitude
 - Low altitude, typically up to 1 000 ft
 - Medium altitude, typically 1 000–18 000 ft
 - High altitude, typically above 18 000 ft
- By take-off weight
- By application
 - Logistical delivery
 - Agricultural applications
 - Commercial structural inspection
 - Military (intelligence, surveillance and reconnaissance and unmanned combat air vehicles)
 - Consumer or hobbyist drone

UAVs in HMA

UAVs have particular applicability in HMA especially during NTS and TS phases. They can be equipped with visible light electro-optical cameras, thermal imaging systems and LiDAR sensors. This gives them the principal advantage of being able to observe remotely and sense terrain without placing a human operator into hazardous circumstances. UAVs can cover areas quickly and this can help in the early stages of NTS.

Perhaps the greatest contribution of UAV-mounted sensors is to assess suspected hazardous areas, enabling scarce HMA resources to focus on a smaller confirmed hazardous area. For incidents involving explosions at ASAs, where explosive ordnance may be projected over wide areas, UAVs are excellent at identifying munitions in inaccessible areas, such as on roofs. A significant issue with UAV-mounted sensors is handling the data produced. This can only be mitigated effectively using automated techniques. This is covered later in this monograph.

Even when legal and authorisation precautions have been taken, the use of UAVs could create problems for the civilians living in the area

One risk of using UAVs for HMA is that distinguishing between civilian and military UAVs is generally impossible. Therefore, in some places, even when legal and authorisation precautions have been taken as recommended in the monograph, the use of UAVs could create problems for the civilians living in the area. These problems include fear that the drone is military, an attack or surveillance-related, psychological impact, possible preventive displacement, panic or be targeted by armed actors (e.g. NSAG, self-defence groups) due to confusion. This should, therefore, be identified as a risk, and appropriate mitigation measures implemented (e.g. notification, preventive public communication and zone or drone marking).

The following factors should be considered when determining the suitability of UAV-mounted remote sensing systems for HMA applications:

- Definition of objectives: Detection effectiveness depends on the size, type and depth of the explosive ordnance. Smaller, deeply buried items are harder to detect. False alarm rates and probability of detection must be assessed, with the ideal being high accuracy and minimal false positives.
- Availability: UAV availability depends on having trained operators and systems that are operationally fit to fly. The logistical sustainability of these systems in remote or austere environments should also be considered.

- **Cost:** Cost and affordability are critical factors in considering the employment of UAVs. Due cognisance should also be taken of the costs of sustaining and maintaining the capability in operational use.
- **Environmental considerations:** Various issues can affect the usability of UAV-mounted sensors for HMA including vegetation, terrain type and features (e.g. watercourses, buildings) and levels of human activity.
- **Effects of weather:** Weather can have a huge impact on the efficacy of airborne platforms and sensors. Generally, low wind conditions are preferred as this improves UAV performance and reduces vibration effects on sensors. Heavy rain and mist may completely degrade the effectiveness of some sensors. Consideration should also be given to the time of day in which sensors are employed to address temperature-dependent effects on thermal systems and shadow on visible light electro-optical systems.
- **Data processing:** UAV-mounted sensors generate data at a prodigious rate and an automated means of processing this collected data must be available.

Since UAVs are dual-use technologies, the procurement of UAVs for humanitarian purposes should be guided by ethical as well as purely economic and technical characteristics. It is suggested that UAVs used within the HMA sector should be acquired from non-military sources and should not be adaptations of currently fielded military weaponised UAVs.

The global consumer UAV market for non-military applications was valued at \$5.12 billion in 2023 and is expected to reach \$15.78 billion by 2032

UAV technology is now mature and UAVs of all sizes and applications are freely available at relatively low cost from a diverse range of suppliers. Given the reduction in size of sensors, even small UAVs can now be used to deliver useful payloads in support of HMA operations.

One consideration in the past that has limited the use of UAV sensors has been the cost of acquiring suitable devices and the associated cost of sensors. Looking specifically at non-military applications, the global consumer UAV market was valued at \$5.12 billion in 2023 and is predicted to grow at a compound annual growth rate of 13.2% between 2024 and 2032, reaching \$15.78 billion by 2032. At the same time, the price per unit is expected to decrease by 3.85% per year.⁴⁷

As UAV and sensor technology improve in terms of technical performance and at the same time reduce in cost, the suitability and applicability of UAVs for HMA is likely to increase.

UAV use in Africa

The use of UAVs in Africa has expanded significantly over the past decade, spanning civilian, commercial, humanitarian and military applications. African governments, private companies, NGOs and international partners are increasingly leveraging drone technology to address infrastructure gaps, improve service delivery and enhance security. Some of their main uses on the continent have included:

- Humanitarian and development use
 - Medical deliveries: Countries such as Rwanda and Ghana have become global pioneers in using drones (e.g. Zipline) to deliver blood, vaccines and medicines to remote or underserved areas.
 - Disaster response and mapping: Drones are used for rapid damage assessments, flood monitoring and mapping in the aftermath of natural disasters or in planning development projects (e.g. in Malawi, Mozambique).
 - Agriculture: In countries such as Kenya and South Africa, drones are employed for precision farming, crop health monitoring and pest control, helping boost productivity.
- Conservation and environmental monitoring
 - Drones assist in wildlife monitoring, anti-poaching patrols and environmental mapping in countries such as Tanzania, Namibia and Botswana.
 - They help monitor deforestation, water resources, and climate-related changes, aiding conservation strategies.
- Commercial and civilian applications
 - Drones are being used in infrastructure inspections, mining, logistics and urban planning.
 - Start-ups across Africa are exploring drone-based services for photography, surveillance and data collection.

However, their use also raises important regulatory, ethical and security concerns. One of the factors often overlooked is the legal implications of owning and operating UAVs. Almost every country in the world has its own legislation and regulations that govern the ownership and use of UAVs. Some African states restrict the ownership of UAVs or impose rigorous licensing procedures on their use, due to the not unreasonable assessment that UAVs may be used for nefarious purposes. Other African states have not yet developed regulatory frameworks governing the use of drones.

From 2015–2018, NSAGs in Libya used small UAVs for intelligence, surveillance and reconnaissance, especially to support the deployment of large suicide vehicle-borne IEDs against government targets. Small UAVs were also used to drop IEDs on

static targets. The photograph shows a small UAV that has been adapted to deliver explosive ordnance and recovered in Libya in April 2018.

Chart 25: Small UAV adapted to deliver IEDs recovered, Libya



Image source: Twitter (original author not identified)

Another consequence of the lack of regulation of use of UAVs on the continent is the accidental or intentional invasion of airspace. This can be best shown by the most recent example in April 2025 when the entry of a Malian UAV into Algerian airspace led to a large diplomatic row between the two states and their allies.

It is essential that sufficient attention is paid to the legislative and regulatory issues surrounding the ownership and use of UAVs in a particular country or region. Given the positive uses of UAVs, the AU has a role to play in establishing a mechanism to approve and regulate their use for humanitarian purposes.

Alternative techniques for disposal

As discussed earlier, in addition to detection, the most common disposal methods come with their own challenges. Developing safer, more efficient and environmentally friendly disposal technologies can enhance the effectiveness of clearance operations while minimising risk to operators and civilians.

Non-explosive methods

The difficulty in procuring high explosives has encouraged some mine action organisations to employ remotely initiated thermal tools to incinerate explosive fillings. Most systems are based on thermite compositions that have the advantage of being a low hazard to store and transport, but when initiated remotely, generate a high temperature jet that readily penetrates the munition casing and causes the explosive filling to ignite. An example of such a tool is shown below. Thermite tools are useful for the following applications:

- High explosive (HE) filled mortar bombs of all calibres
- Thin-skinned HE tank and artillery projectiles, the latter with a calibre of 130 mm or less
- Anti-personnel and anti-vehicle mines of all types
- HE submunitions delivered by rocket artillery or aircraft canisters
- Small HE-filled common-use ammunition, such as fired grenades

Chart 26: DISARMCO Dragon thermal torches⁴⁸



Images credit: DISARMCO

Thermite-based tools have been used to good effect in Africa and are particularly useful for rendering safe smaller ERW. The photograph in Chart 27 shows a POM-2 scatterable anti-personnel mine that was rendered safe using a thermite tool in Libya. In this case, the explosive content was destroyed by burning and the main charge did not detonate.

Chart 27: POM-2 AP mine rendered safe, Libya



Image credit: Free Fields Foundation

Binary liquid explosives

An alternative approach to addressing the problem of storing and transporting explosives is to employ liquid binary explosive compositions, the components of which are non-explosive to store and transport and only become a high explosive when mixed at the point of use. An example of an explosive tool that uses a nitromethane-based binary liquid explosive is shown below.

Chart 28: J-Etna employed against a BL-755 submunition⁴⁹



Image credit: Alford Technologies

The principal advantage of using binary liquid explosives for mitigating explosive threats is that the materials until mixed at the point of use are non-explosive. Therefore, they are much easier to transport by road and air. They are also much cheaper than conventional military explosives and they only retain their sensitivity for a short period of time after preparation, thus they pose a lower diversion risk and are less likely to be misused in IEDs. The constituents of binary explosive compositions are widely available.

Explosive harvesting

Earlier sections highlighted the difficulties of acquiring high explosives to undertake the safe disposal of explosive ordnance. An alternative approach, which has been implemented in Cambodia, is to harvest explosives from available ERW and unserviceable HE munitions. Golden West Humanitarian Foundation and the Cambodian Mine Action Centre have over 15 years of experience in the safe operation of an explosive harvesting system (EHS) and have recovered military explosives from a wide range of HE projectiles, aircraft bombs and missile warheads. This recovered explosive has been used for the manufacture of demolition charges, which HMA actors have used to dispose of mines and UXO.

Chart 29: Remotely operated bandsaw for munition cutting⁵⁰



Image credit: Golden West Humanitarian Foundation

The Golden West Humanitarian Foundation EHS concept is based on the remotely operated use of cutting equipment to gain access to the munition explosive filling. Typically, this is in the form of a transverse cut. Once access to the explosive filling has been achieved, the cut munition is placed in a steam jacket to facilitate the melt-out of the explosive filling as shown below.

Chart 30: Extraction of explosives by steam melt-out



Images credit: Golden West Humanitarian Foundation

Once the explosive composition has been melted out of the munition body, it is blended with other recovered explosives to produce a material with the required characteristics. The explosive is then poured into a mould to cast the finished demolition charges as shown below.

Chart 31: Casting of demolition charges



Image credit: Golden West Humanitarian Foundation

The final stage in the manufacturing process is the drilling of the detonator well and the application of a batch label.

Chart 32: Manufactured 100 g demolition charge



Image credit: Golden West Humanitarian Foundation

The principal advantage of implementing an EHS in Africa is that it would provide an urgently needed and sustainable source of demolition explosives to facilitate the reduction of explosive hazards. The use of EHSs helps reduce unserviceable munitions stockpiles, limits the risk of diversion and IED proliferation and lowers the explosive threat posed to civilians by ERW and unserviceable explosive ordnance. By providing locally sourced demolition charges, the logistical sustainability of explosive clearance operations is simplified and the costs of donor-funded clearance operations reduced.

The use of EHSs allows demonstrably safer explosive ordnance disposal operations to be conducted by facilitating the on-site destruction of ERW and removing the need for explosive ordnance disposal teams to move hazardous items. The presence of an EHS reduces the risks to future donor-funded explosive hazard reduction programmes by ensuring that a reliable local supply of demolition explosives is readily available. EHSs allow the metal components of explosive munitions to be recovered and recycled.

IMAS and new technologies

While all the technologies discussed here have made progress, their usage and acceptance within the sector remains limited. Several UN-sponsored publications cover NTS,⁵¹ TS⁵² and related personnel competency standards,⁵³ and IMAS

provides a generic guide on the procurement of mine action equipment.⁵⁴ The HMA domain is generally characterised as one that is supported by scarce donor funding, and most mine action organisations employ well-proven technology solutions with low technical risk. The fact that the IMAS guide to the procurement of mine action equipment has not been updated since 2013 is an indication of the low priority traditionally afforded to acquiring technologically advanced solutions in the HMA sector.

A significant issue is that the publication of mine action standards lags behind technological developments by a considerable degree. There are no published standards that cover the employment of UAVs in mine action and there are no standards or test and evaluation protocols that cover the employment of airborne sensors. Unsurprisingly, IMAS does not yet address the issue of computer-based imagery analysis or AI in tackling what has been termed the 'Gordian Knot' in mine survey and clearance: achieving sufficient confidence in the technologies and methods employed.⁵⁵

Chapter 6

Candidate areas for technology insertion

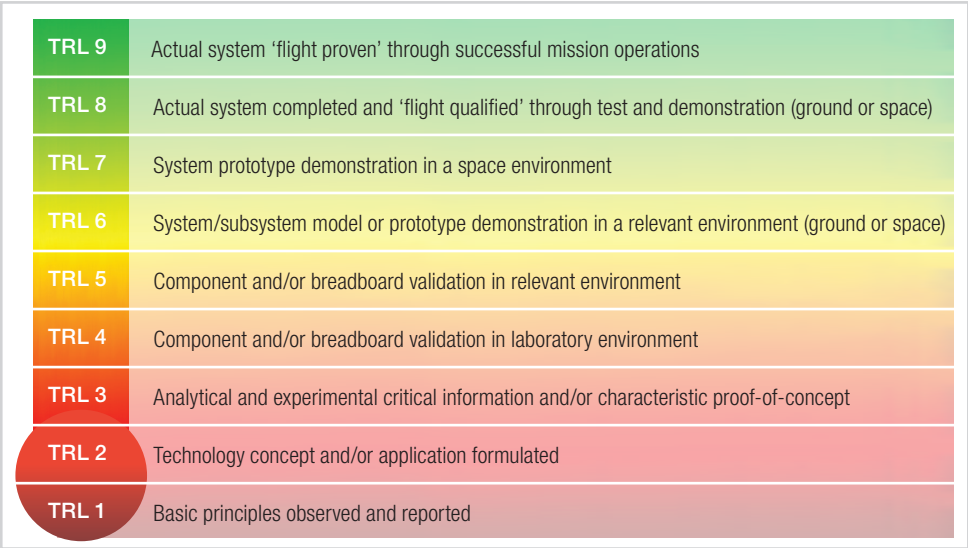
This final section of this monograph identifies the principal requirements and constraints that should guide the delivery of new technologies for HMA in Africa. It summarises the candidate technologies that could be deployed with an acceptable level of risk. It should be noted that African states have a diverse range of technical capabilities, and it is impossible to make Africa-wide recommendations.

Key requirements and constraints

Technology readiness

A key consideration for assessing the suitability of any new technology is a realistic assessment of the technical maturity or readiness of the technology. NASA uses a concept of technology readiness levels (TRLs) to assess technical maturity for its projects. An overview is shown below.⁵⁶

Chart 33: NASA TRLs



Source: NASA

For the HMA domain, technologies at TRL 1–TRL 4 are principally concerned with technology demonstration in a research or academic environment. At TRL 5, the technology is ready for evaluation in an operational environment. It is only at TRL 8 or 9 that a technology may be considered for full, unconstrained deployment in an operational HMA environment. In considering deploying any new technology to support HMA in Africa, it is recommended that the TRL of the technology is at or above the following levels:

- TRL 5 for capability evaluation under controlled conditions in an operational environment
- TRL 8 or 9 for full operational use

To progress from TRL 5 to TRL 9, a technology must be thoroughly demonstrated and tested under realistic operational conditions to fully understand its characteristics and limitations. Ideally, the introduction of new technology should be accompanied by an appropriate IMAS or a test and evaluation protocol.

Affordability

The world is replete with examples of technology that one day could deliver huge benefits to humankind, if appropriate resources and time are invested. In the HMA domain, it is critically important to recognise that resources are invariably constrained and becoming more so, and that only technologies that provide a demonstrable operational benefit should be deployed.

In considering the fielding of a new technical capability for HMA, a thorough business case should be developed, and it should cover the capital costs of acquisition as well as the support costs (including maintenance, spares and any consumables). The business case should include a description of the operational benefits to be accrued by using the new technology. This could be in the form of a cost-benefit analysis using discounted cashflow techniques if the technology is to be deployed and used over multiple years. In summary, new technology should only be introduced if it is affordable, appropriately funded and delivers defined operational benefits.

Sustainability

The sustainability of technology is an often-underestimated aspect when new systems are introduced. In the Africa context, where HMA operations often occur in low-capacity and conflict-affected settings, logistical sustainability is essential. This includes ensuring the availability of spares and ancillary equipment to support the system. Consideration must be given to the availability of trained personnel for

system maintenance, as well as essential resources such as power and water to sustain operations. While new technologies may be introduced for well-defined short-term operational trials, the long-term fielding of new technologies must consider sustainability.

Legislative and regulatory approval

The use of many technologies is subject to legal and regulatory constraints, and Africa is no exception. Dual-use technologies, such as explosives and UAVs, are often tightly controlled. It is essential that consider national laws, regulations and licensing requirements before introducing new technology.

Detection technologies

Visible light camera systems

High-resolution visible light camera systems have much to offer HMA in Africa, and such systems are widely fielded for use in NTS and technical survey (TS) applications. As sensor resolution increases, so does the quantity of data collected thus appropriate attention must be applied to automated data analysis. Visible light camera systems, including those mounted on UAVs, should be considered a mature, TRL 9 technology for HMA applications in Africa.

This type of sensor is also the most affordable, with acquisition costs decreasing over time as pixel size and resolution improve. This technology is also widely available and is probably more robust and repairable than the other sensor technologies considered in this monograph. In terms of legislative and regulatory approval, there are few limitations on the employment of these sensors.

Thermal imaging systems

The use of thermal imaging systems has been shown on operational field trials in adverse and austere environments, and the technology has strong potential to support HMA operations in Africa. It is particularly applicable in desert and semi-arid environments, where dense vegetation is absent. Thermal imaging should be considered a TRL 8 application for HMA applications in Africa.

Thermal imaging sensors are generally up to 10 times more expensive to acquire than conventional visible light camera systems. The technology has advanced markedly in the last two decades, and sensors no longer require cryogenic cooling to provide satisfactory performance; this has significantly improved the sustainability of thermal imaging in austere operating environments. The key regulatory implication of employing thermal imaging sensors is that it is a technology that has a dual-use military function and the use of high-resolution sensors in some countries is strictly controlled.

LiDAR sensors

LiDAR sensors have a similar level of technical readiness to thermal imaging systems, and they have shown great potential when used on operational field trials in Africa. The technology probably has most relevance in supporting NTSs and TSs, particularly in highly vegetated areas and allows the ground beneath vegetation to be imaged. LiDAR should be considered a TRL 7 or 8 technology for HMA applications in Africa.

LiDAR systems are technically more complex than visible light camera and thermal imaging systems and are correspondingly more expensive to deploy. LiDAR systems generate vast amounts of data, requiring substantial storage and processing capacity, which raises concerns about sustainability. LiDAR systems are complex and delicate, requiring careful handling; damage often necessitates returning the sensor to the manufacturer. Furthermore, as LiDAR systems contain laser emitters, there are regulatory issues to be addressed, particularly if the laser used within the LiDAR sensor is not classified as 'eye safe'.

Information processing

Information processing requirements are often overlooked in HMA. The introduction of remote sensing capabilities mandates that a form of automated data processing is used to address the data deluge and prevent human operators from being overwhelmed by a morass of raw, unprocessed data.

Several operational field trials have shown the applicability of deep learning and AI for the analysis of sensor data used to aid in the detection of mines and UXO. The TRL of these AI-based systems is at TRL 7 or 8. There is still some work to be done to improve the probability of detection and to reduce false alarm rates when these tools are applied to imagery acquired from visible light camera systems or thermal imaging systems.

UAVs

While not a detection technology, UAVs are important enablers of remote sensing. Commercial UAVs have come of age over the past three years, and UAVs of all sizes and types are readily available at acceptable cost. The ability of UAVs to carry sophisticated sensor systems has been shown in a wide variety of applications. UAVs have significant potential for use in HMA applications in Africa and are at TRL 9.

UAVs of various sizes and capabilities are available from a number of commercial vendors. Cost is very much a function of payload size and mission duration. Most UAVs are now of modular construction and a degree of on-site repair is possible for components vulnerable to damage during operational use. There are, however,

significant legislative and regulatory issues to be addressed with employing UAVs in some countries.

Disposal technologies

This monograph has highlighted the difficulty associated with acquiring serviceable explosives in low-capacity and conflict-affected countries. The following methods offer potential alternatives to facilitate the safe disposal of explosive ordnance.

Non-explosive methods

The principal non-explosive means of explosive disposal is the use of thermite-based tools. These tools are available from several suppliers and offer significant advantages in terms of transport and logistics for HMA operations in Africa. Thermite-based explosive ordnance tools should be considered a TRL 9 technology for HMA applications in Africa.

They are readily available and relatively inexpensive when compared to the use of HE donor charges. The constituents of thermite tools are generally non-toxic and provide a safe and sustainable method of disposing of explosive ordnance. A key emerging issue is that thermite-based tools are being classified as Class 1 dangerous goods (hazard code 1.2G) by some regulators, making it more difficult to ship them by air.

Binary liquid explosives

Binary liquid explosives offer significant advantages over conventional military explosives for use in HMA applications. They are cheaper and much easier to transport by air or road and have the advantage of only becoming an explosive hazard when mixed immediately prior to use. They also offer a lower risk of diversion and misuse as mixed explosive compositions only retain their explosive sensitivity for a relatively short period of time. Binary liquid explosive tools should be considered a TRL 9 technology for HMA applications in Africa.

Binary liquid explosives have the advantage of
only becoming an explosive hazard when mixed
immediately prior to use

Binary liquid explosive compositions based on sensitised nitromethane are very affordable when compared to conventional military high explosives. The fact that the constituents of binary explosive compositions can be sourced widely underpins their sustainability and explains why their use is becoming more prevalent in HMA applications. Nevertheless, binary liquid explosives are still explosives and are subject to extant legislation and regulations in most states.

Explosive harvesting

EHSs offer an alternative approach to addressing the shortage of serviceable explosives to carry out the safe disposal of UXO. EHS harvest explosives from military munitions in a safe and methodical fashion and produce consistently sized demolition charges for use in HMA operations. EHS technology has been proven in Cambodia and has resulted in the production of almost a million demolition charges. EHSs are especially useful in Africa countries and regions with significant stocks of ERW. EHSs should be considered a TRL 9 technology for HMA applications in Africa.

The technical components of a viable EHS are relatively inexpensive; the main cost lies in the physical infrastructure needed for storing and processing high-explosive munitions. EHSs represent a very good example of practical resource re-use and recovery, as all resources associated with the explosive harvesting process can be re-used. The key legislative and regulatory hurdles associated with the implementation of EHSs are that it involves the processing of high-explosive filled military munitions and generates conventional high-explosive demolition charges.

Chapter 7

Recommendations

Based on the current state of technological advancement in the HMA sector, as outlined in this paper, the following key recommendations are proposed:

For the mine action sector

- Accelerate the development of IMAS and technical notes on UAVs, remote-sensing and AI, ensuring legislative, ethical and environmental considerations are taken into account
- Share results of pilot and test projects to support ongoing innovation and build a repository of best practice

For the private sector

- Collaborate with the HMA sector to adapt and guide technologies for humanitarian use

For African states

- Develop legislation to support testing and deployment of UAV, remote sensing and data processing technologies
- Invest in new technologies through funding or pilot opportunities
- Facilitate testing and implementation through timely authorisations and deployment support

For the African Union

- Encourage intra-African collaboration on technology across sectors
- Facilitate the development of model laws regulating UAV, remote sensing and AI among member states

For donors

- Maintain adequate and sustainable funding for technology development in HMA to enable faster clearance, cost efficiency and greater humanitarian impact

Notes

- 1 ICRC, Drones, infrared cameras and AI join the search for mines, 16 June 2020, <https://blogs.icrc.org/inspired/2020/06/16/drones-infrared-cameras-mines/>.
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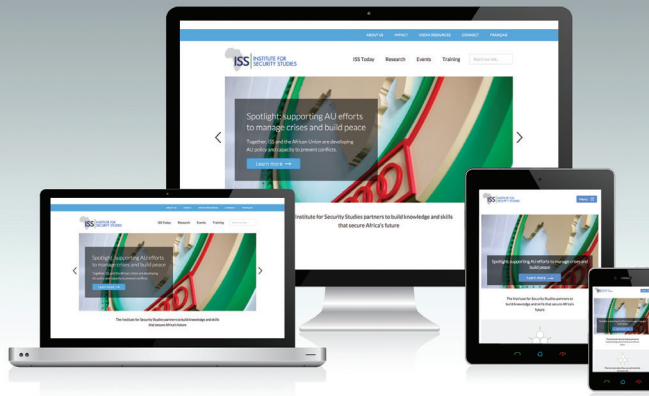
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Humanitarian mine action programmes in Africa face severe funding cuts in 2025, threatening operations across the continent. This monograph examines how emerging technologies can enhance Africa's explosive hazard response capabilities. It analyses airborne remote sensing, artificial intelligence-powered data processing, and unmanned aerial vehicles for detection activities that could accelerate land clearance operations. The monograph addresses regulatory frameworks, technology readiness, affordability and sustainability challenges facing African states seeking to modernise their mine action programmes through practical technological solutions.

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