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RESEARCH ARTICLE

Eliminating Hidden Killers: How Can Technology Help Humanitarian Demining?

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Despite twenty-first-century technological advances by Western militaries for demining and the removal of improvised explosive devices, humanitarian demining relies mostly on mid-twentieth-century technology. While international legal efforts to curb the global use of landmines have been quite successful, constraints on humanitarian demining technology mean that unfortunate and preventable deaths of both civilians and deminers continue to occur. Developing devices and technologies to help human deminers successfully and safely carry out their work is a major challenge. Each phase of the physical demining process (i.e., vegetation clearance, mine detection, and removal) can benefit from the development of demining technologies. However, even with the prospect of "smart" demining technology, the human aspect of supervision remains a crucial challenge. Although current research and development hold promise for the future of humanitarian demining, the barriers to progress in the field are more than technical. The prioritization of military operations, a lack of coordination between governments and humanitarian actors, a tendency towards secrecy, and an underlying lack of funding are just some of the roadblocks to eliminating the yearly death toll associated with humanitarian demining, in addition to other impacts on post-conflict societies. This paper calls for new ideas, renewed innovation, and new sources of governmental and non-governmental support for this often-neglected aspect of international security.

Introduction

Landmines remain deadly decades after wars end. They continue to impact some 60 countries around the world. Annual reporting shows the gravity of the problem: thousands are killed or injured each year, primarily civilians, of which nearly half are children (International Campaign to End Landmines – Cluster Munition Coalition 2018). The removal of this threat to life, limb and property falls to mostly humanitarian demining efforts. Some research and development (R&D) has been initiated since the 1997 Anti-Personnel Mine ban ("Ottawa Treaty") but most of these projects have been unworkable, underfunded, or underexploited. Technology adoption and innovation have not received sustained support. The humanitarian community relies primarily on mid-century, World War II-type technologies, i.e., primitive hand-held metal detectors and bayonet-style tools, to find and remove landmines when it should be possible for modern technologies, tools, and machines to

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do the work, or at least actively assist demining efforts. The humanitarian imperative calls for it.

Multi-faceted demining machines — remote controlled or semi-autonomous — should become available in the future to perform some human mine-clearing activities and improve upon them, making life safer for deminers, and speeding up the demining process. Eventually, these "robots" could do each of the three major stages of removing mines once the demining site has been located[1]: preparing the ground (e.g., vegetation clearing, obstruction removal); mine detection (along with other explosive hazard detection); and mine removal by excavation or destruction in place (e.g., burning, freezing, or exploding). Although the all-purpose, entirely autonomous robot may be decades in the future, primitive devices are already on the market, but they need considerably more development, testing, and cost-reduction before they can be widely used to carry out one or more of the three demining steps once a mine-infested area has been identified.

The initial technical survey to find the most likely locations of mine fields can be greatly aided by technology. Testing work using unmanned aerial vehicles (UAVs) has started to extend experimentation from basic survey work (e.g., as part of planning) to examining fields with advanced sensors before mine clearance begins (see **Table 1**). Work done by Norwegian People's Aid, for example, conducted initial testing and validation flights (Lisica et al. 2019). Advanced image classification and recognition using machine learning/artificial intelligence has been used to identify areas with likely mines (e.g., Adlešič and Zobundžija 2019; Krtalić, Racetin and Gajski 2018). Once an area is identified for clearance, other technologies can then be used.

Preparing the Round: Vegetation Clearance

The clearance of surface vegetation and other obstructions can sometimes be more time consuming than the clearance of the landmines and other explosive remnants of war (ERW). In one case, the Cambodian Mine Action Centre estimated that 70 percent of its landmine clearance effort is vegetation removal, due to the difficult terrain and the risks to operators from tripwires, poisonous snakes, and mosquito-borne diseases (Ueno et al. 2013). Of course, in different sites, there may be significant variations in vegetation and ecological complications, e.g., the forests of Croatia (Adlešič and Zobundžija 2019). The disturbance of local animal habitats also needs to be taken into account.

Remote-controlled machines are beginning to be used more frequently in order to prepare ground for deminers, especially to clear vegetation. These unmanned ground vehicles are getting smaller, more effective, and economical — moving away from the manned military behemoths that are so

Table 1: UAV Applications for Technical Survey.

Technical Survey Role	Description
Assist in planning of demining operations	Selection of appropriate tool; selection of the best technical survey path; analysis of environmental conditions of terrain; identification of likely mine locations
Monitor demining operations, report on progress and completion	Monitor mine action operation progress, estimate completion date, progress documentation
Map demolitions and identify patterns	Completion documentation, identification of possible patterns for future survey work

Source: Based on senseFly (2016: 5).

costly to transport, maintain, and operate that they frequently go unused in humanitarian demining (Smith 2017c: 1).

Mini-flails are a promising new machine in demining and small "area preparation machines" are also arriving on the market.[2] One remote-controlled vehicle, known as an area preparation tractor, is based on an Italian vineyard tractor, with added armour and blast-resistant wheels (Smith 2017b). It can clear vegetation far in front of manual deminers and is powerful enough to climb hills but small enough to manoeuvre between large trees, while continuously removing vegetation and small trees. The vehicle has the added advantage of knocking the fuses off fragmentation mines (or initiating them), thereby reducing the hazard for the clearance teams that follow. They are designed for humanitarian demining applications specifically, rather than military applications, i.e., they are not designed to withstand anti-tank mines (Smith 2017c).

Another useful tool is the excavator like the Arjun Demining System, that rakes through the soil to a depth of 20 cm using a back hoe. Most mines can be seen by the operator as they drop from the raised rake and are moved with the rake (GICHD 2012). Although it does not completely eliminate the threat of mines — deminers examine and hand rake the ground to search for additional mines — it is regarded as exceptionally cost-effective humanitarian demining equipment (Smith n.d.).

Mine Detection: Finding Hidden Killers

Once vegetation is cleared, deminers must painstakingly check every square centimetre of the ground to a minimum UN-mandated depth of at least 20 cm with almost complete certainty, sometimes specified as in excess of 99.5 percent (United Nations Mine Action Service [UNMAS] n.d.).

Basic metal detectors have, since World War II, been a standard tool for mine detection. They have induction coils at the end of hand-held rods, like the ones used by treasure hunters and beachcombers. One truly significant advance in recent decades was the addition of electronic filters to reduce the "ground noise" of these field-deployed devices. But even so, the problems with this technology are many: they can be set off by virtually any kind of magnetic metal, including from the numerous metal fragments or debris that litter former conflict zones; the metal detectors produce many false-positive signals (false alarms) and occasionally also produce dangerous false-negative signals (especially for deeply buried mines, where the metal remains undetected). They cannot reliably detect all mines, especially those with minimum metal, at all necessary depths.[3] As a result, much more innovation is needed.

A major source of potential innovation is the recent progress in military demining and improvised explosive device (IED) detection. Over the past two decades, Western militaries have made considerable efforts to deal with the major challenges of IEDs, which were causing the deaths of so many soldiers. NATO nations prioritized three major pillars to their counter-IED work: "Defeat the Device," "Attack the Networks," and "Prepare the Force," supported by a robust intelligence process (NATO 2011: fig. 1.3). This combined effort places the emphasis on major advances in technology, including miniaturization, reliability, geomatics (i.e., inbuilt GPS), ergonomics, and ground-compensating technology. These efforts have saved many soldiers' lives.

Another significant development is ground penetrating radar (GPR). This detection technology is the nearest to standard deployment in humanitarian demining. In dual-sensor devices, after a metal-detector sends an alert (usually an audio squeal), the deminer can turn on GPR. The GPR-head sends electromagnetic (radio) waves into the ground and the reflected-wave intensity gives a sense of the size and rough shape of the detected object. Metal clutter can usually be disregarded. Resolution has historically been quite poor and GPR imagery and readouts required user interpretation, which carries its own risks.[4]

Recent technological developments have built on decades of experience to decrease by an order of magnitude the false alarm rate, giving rise to the hope that "hand-held detectors are moving to the point where they can discriminate what the detected object may be" (Peyton et al. 2019: 31). Further research has started to make feasible lower-cost, lightweight, multi-band radars used in conjunction with metal detectors to "see" small objects buried at close range (Šipoš, Malajner, and Gleich 2019). Issues remain around radar head and power requirements adding weight, cost, and technological complexity to the hand-held device. Nevertheless, they can prove cost-effective by reducing false alarms, increasing clearing speed, and reducing the clearance cost per square metre.

When deployed on vehicles, GPR systems can be more powerful and allow side-scanning as well as vertical scanning, thus increasing the resolution to a level that can reliably detect anti-tank mines or IEDs. Hopefully, vehicle-mounted anti-personnel mine detection systems for real-time 3D subsurface visualization will become user friendly and commercially available. That technology has probably already been developed for the US military, but such devices remain highly classified and restricted to the military domain.

Despite these challenges, some hand-held dual-sensor detectors are already on the market.[5] They have been demonstrated in field tests and praised for their capabilities and increases in productivity by organizations such as The HALO Trust (Boshoff and Cresci 2015; The HALO Trust 2011), while other advances continue apace with related technology (Sato 2019). However, these advanced devices are expensive and are mostly purchased by military forces, which have different needs and priorities. Humanitarian deminers must do more than cross a minefield to reach a military objective; they have to dig up all the mines and explosive hazards in an area while posing little or no risk to themselves, as their objective is to completely clear the mined land.

Militaries have found that dual- and multi-sensor detectors have been very useful against the modern IEDs, given that the IEDs generally have small amounts of metal, which provide the first indications of a buried threat, before the GPR or other sensors are used to find the much larger buried plastic elements of the device.

As indicated in **Table 2**, humanitarian deminers need to ensure that the land can be declared "clear" (with virtually 100 percent certainty) for civilian use, including for intensive farming. Before returning the ground to locals, deminer chiefs often walk the ground themselves to show locals that the ground is safe.

Newer, more exotic detection technologies will likely be deployable one day, but these

Table 2: Comparison of Military and Humanitarian Deming.

	Military Demining	**Humanitarian Demining**
Purpose	Rapid military passage (e.g., breaching mine fields)	Long-term restoration of land for civilian use
Timing	During war/conflict	After war/conflict, during reconstruction
Clearance goal	70–90%	Virtually 100%
Devices (current usage)	Heavy vehicles (e.g., with flails, rollers, and excavators), advanced technology (including multi-sensor detectors, vehicle-borne and handheld)	Primarily metal detectors, handheld prodders, simple tools

Source: Adapted from Furihata and Hirose (2005: 338).

are not yet mature or cheap, nor simple enough for widespread use in humanitarian demining applications. Some technologies may never be practicable. The drawbacks of many R&D technologies include complexity and high cost for a market with a limited customer base. Furthermore, despite claims from researchers, some technologies have not yet proven their utility or practicality, for example, infra-red imaging, X-ray backscatter, acoustic/seismic reflection or vapour sensing. A larger set of detection methods is provided in **Table 3**. For multi-sensor systems, the various outputs can be fused

Table 3: Mine Detection Technologies.

Method	Maturity[6]	Cost and Complexity	Benefits	Concerns/Problems
Metal detector	In use	Low	Much experience	High false alarm rate (debris); minimum-metal mines hard to detect
Ground Penetrating Radar (GPR)	Available commercially	Medium	Gives size and shape info; increases clutter-rejection rate	Poor resolution (fuzzy images); extra weight; danger of mischaracterizing a mine
Dual sensor (metal detector + GPR)	Available commercially	Medium	Gives useful info before excavation	See above
Infrared (passive or active)	Medium term	Medium	Lightweight; useful for initial survey, especially used at night	Poor resolution and ground penetration; effect dissipates quickly over time
Millimeter wave	Long term	Medium	Subterranean imagery	Interpretation difficulties; water anomalies
Acoustic/seismic (including ultrasound)	Medium term	High	Ultrasound penetrates very wet heavy ground, 3D imagery	Slow, high false-alarm rate
Magnetometer	Near term	High	Deep detection	Only detects ferrous materials
UAV platform	Near to long term	Medium-high	Potentially accurate source of information before excavation; speed	Remains unproven and experimental
Trace explosive (vapour) detection				
Trained dogs	In use	Medium-high	Proven accurate and dependable	Significant training needed; only justifiable in a long-term programme
Other animals	Medium term	High	Potentially accurate	Unproven as yet; difficult to train; undependable; difficult to interpret

(Contd.)

Method	Maturity[6]	Cost and Complexity	Benefits	Concerns/Problems
Chemical sensors (including biosensors)	Medium term	High	Widely used in industry for other applications	High false alarm rate; slow analysis; remote analysis increases error and time
Bulk explosive detection[7] (using nuclear sources)				
X-ray backscatter and X-ray fluorescence	Medium term	High	2D images	Shallow soil penetration
Thermal neutron activation	Near term	High	Better for anti-tank mines	Limited depth penetration; large device; loss or theft of radioactive sources
Nuclear quadrupole resonance	Long term	High	Clutter does not cause false alarm	TNT not as well detected as RDX; interference from radio waves; bulky

Source: Review of the literature and based on similar tables (Bruschini and Gros 1997; Ghaffari et al. 2004; Sato 2006; senseFly 2018).

for automatic target recognition, using special signal-processing techniques, including fuzzy logic, neural networks, and 2D/3D texture analysis. The devices could eventually be miniaturised in a handheld device or a small vehicle. Some sophisticated sensors are already used in military vehicles. And commercial mining for precious minerals already employs an array of useful technologies that could be adapted, including handheld X-ray fluorescence devices.

Various innovative sensor technologies have been explored for humanitarian demining, including those that use animals as sensors. Attempts to use bees, although once ridiculed, have shown limited potential (Hadagali and Suan 2017; Simić et al. 2019). Rats as sensors, on the other hand, proved to be more hype (Fears 2017; Kalan 2014; Sullivan 2015) than practical (DeAngelo 2018; Fast et al. 2017; Smith[8]). By contrast, dogs have long been effectively used in demining but they are time-consuming to train, difficult to maintain, and quite expensive.[9] While dogs can detect many explosives reliably, they have to operate in the working context, with training reinforced daily, especially to clearly indicate the threat; as a result, mine-sniffing dogs, although they may be friendly, are often neither cheap nor easy to work with. Experiments are under way to use free-running dogs equipped with GPS, cameras, and radio contact for technical surveys of large areas (Bold 2014: 12–14; Lisica and Muftić 2019).

Mine Removal: Extraction or Explosion?

While the military can tolerate the risk that not all mines are removed, humanitarian deminers work to a significantly higher standard. They seek to clear a field of all explosive hazards, including mines and any other ERW (Habib 2007: 152). When a metal object is detected, the standard procedure in humanitarian demining is to start digging some distance (e.g., 20 cm) from the mine at an angle of less than 30 degrees to the ground (ibid.: 167). Simple devices such as handheld garden shovels, rakes, and prodders are used. To overcome ground friction, both hands are frequently used to gently push and scrape, while being careful not to set off the mine on the approach. The loosened soil is scooped away, and prodding/scraping continues until the standard detection depth is reached. The deminer then starts to move the prodder slowly forward towards the location discovered by the mine detector and indicated by a marker (e.g., a bright "casino-chip" plastic marker). The mine is exposed using hand tools that "detect" the mine by feel at angles less than 30 degrees so as not to push on the mine's top pressure plate. This is dangerous work that could eventually be done by machines.

The dangerous process of lifting a mine could also be done by autonomous or user-operated robots in the future (Hemapala 2017). Of course, lifting pressure-operated mines must be done with extreme care, especially if the mine includes an anti-lift device or is booby trapped, e.g., with a grenade underneath whose pin has been removed so it will detonate shortly after the mine is lifted. A hook is sometimes placed (gently) under the far side of the mine before it is "pulled" from a relatively safe distance using a hook-and-line system to trigger any booby trap. But this remains dangerous and risk-intensive work. Typically, when a mine has been safely lifted, it is then moved to a demolition pit, where demolition charges are used to detonate and destroy it.

Not Machines versus Humans, but Machines Serving Humans

To be sure, there are clear benefits of using human deminers. They have a learning and computing capacity combined with self-preservation instincts that far exceed the world's best computerised robots at present. Deminers are mostly from the local population in a post-conflict environment; these non-combat jobs enable them to support themselves, their families, and their communities. They can bring in a real income (albeit often shamefully small) to help stimulate the local economy and so promote wider peace-building efforts. Humanitarian demining funding should include the local beneficiaries and help to empower them. Appropriate mine clearance machines, coupled with proper operator training, can do that by making the deminers' jobs easier, safer, and faster — and help give them better control of their future.

It is equally important to avoid a highly expensive "military" approach that applies the most high-end and high-tech "solutions" but rather to organically develop tools that humanitarian deminers can work with. Andy Smith states from experience: "We should start from where the recipients are, then help them move towards where they want to be. That does involve using computers and sophisticated equipment — but step-by-step and respecting their priorities rather than just imposing ours."[10] This is echoed in the literature as well: "The 'robotic solution' becomes a[n] engineering job' dependent on 'imported devices where the know-how is not available. The increasing cost of the sophisticated devices incorporated in to the robotic devices making very high initial investment and low return on investments. [...] Mainly robots work well for clean and reliable tasks" (Hemapala 2017: 3–4).

Small improvements to simple demining tools can be remarkably effective, such as long-handled ergonomic rakes, but these can be complemented with more advanced technologies and, in some areas, replaced by them (Furihata and Hirose 2005). It is not a case of human versus machine but one of machines increasing human efficiency and effectiveness, as well as safety and security. The traditional "mechanical assistance" in humanitarian demining should expand to include "technological assistance" as well. This would be an integrated solution, with all components (animals, insects, devices, and humans) working holistically.

Towards "Smart" Demining Machines

Eventually, smart technology should advance to the level where it could do much, although not all, of what a human deminer does. The devices would need to be human-controlled or supervised from a distance, with the machine doing the dangerous, labour-intensive work, and suffering the risk of explosions; the person removing and fixing damaged devices would be far out of the area of danger.

One system envisioned by the author would work on an overhanging boom or rail that extends along an area to be demined, e.g., a stretch alongside a road, and then systematically moving further into the field, row by row. The first device on the boom or rail would cut and remove all vegetation up to a certain height.

The second device (possibly a multi-sensor detector built into the first device) would pinpoint the mines or suspicious items in the ground, including by subterranean viewing from different angles on the boom. The precise areas would then be marked by spray-painting or by dropping (lightly) brightly coloured plastic chips. In addition, positions would be recorded by the computerized system using a differential-GPS or another accurate coordinate recorder. The third device on the boom or rail would be a sophisticated extractor, which would dig into the earth much as a human deminer would, employing highly tactile sensitivity. It would remove earth until the mine or metal object is exposed and then, after a human gives the go ahead, the machine would sound a warning to those around and slowly remove the mine or other explosive hazard. This type of envisioned system would mirror a suite of already-operational technologies and tools in use. If the machine encounters a sophisticated problem as it progresses, it should be able to signal a human to examine the problem, e.g., a deminer viewing the area by remote-controlled cameras on the device.

To verify that a thorough job has been done, the fourth device on the boom could do the quality assurance (QA). It could use sensors to detect if another mine had been buried beneath the first. The QA sensor could also scan the lane and conduct tests at selective points. It could apply pressure to the ground to test that no unexploded mines remain. Only then could a lane be declared successfully "cleared" before the demining machine is moved one lane forward. Of course, input from deminers at each stage of the R&D process should be sought.

Conclusions: The Need for Innovation

Given that the advanced systems and technologies described above may run into problems in some difficult field conditions, the preliminary or prototype devices could be used for the easier demining projects at first. The devices could cover soft homogenous ground containing few obstacles where detection and removal are easier. As the technology matures, future models could be deployed to areas containing more complex mixtures of landmines, shrapnel, anti-tank mines, unexploded ordnance (UXO), abandoned explosive ordinance, and IEDs. They could be designed to withstand different climates, and work in difficult soil and terrain.

Given the range of possibilities, one might wonder what has inhibited technological progress so far. Factors include: prioritization of military missions (e.g., in Iraq/Afghanistan); military secrecy and information classification (of both R&D and deployed systems); lack of multi-year funding for humanitarian demining; the small niche market for humanitarian demining that produces little profit; the inability to move from R&D to practical commercial devices; a bureaucratic short-term approach to cost-efficiency; over-hyped proposals that did not live up to expectations; cynicism of innovation by those convinced their current practices are entirely sufficient; governmental/humanitarian actors not sharing information; and an inclination to avoid experimentation or being innovative.

Importantly, the robotics and artificial intelligence revolution is just beginning to be felt and understood in human society more generally. Many potential uses have recently become visible and commercially viable, from autonomous vacuum cleaners to advanced UAVs, but much more is still to come. Demining is an area where such products can be life-saving. Since 2005, the US military has developed and deployed very sophisticated technologies for IED detection and removal that have saved soldiers' lives in Iraq and Afghanistan. Remote-control robots like the "TALON" series of unmanned ground systems have figured significantly in military operations (Wells and Deguire 2005) — and Hollywood depictions[11] — with cutters and grabber assemblies to help deal with IEDs and UXO, as well as options for a range of other such tools, e.g., GPR (Chemring Group 2019b). Many of these technologies could be used or modified for humanitarian demining — some already are (Fardoulis et al. 2018), yet many technical details remain highly classified. However, there is bound to be some spillover as the companies producing the military hardware look for new markets.

There is additional reason to be hopeful: the emphasis on demining R&D is returning after the diversion away from humanitarian support after 9/11 and the Afghanistan-Iraq missions. In recent years, new initiatives and programmes have been launched. The UN Department of Peace Operations (which includes the UN Mines Action Service or UNMAS) has accepted the recommendations of the Panel of Experts on Technology and Innovation in UN Peacekeeping, which include new demining technologies, especially to enhance the mobility of peacekeepers (UN 2015). The European Union is supporting R&D programmes to examine wide-ranging technologies, including aerial drones for survey work, GIS, robots, multi-sensor detectors (including animals and biomimicry), vapour sensors, and small/miniaturized demining machines (European Union 2016). NATO's Science for Peace and Security Programme is supporting activities in Partnership for Peace nations (NATO 2016). Japanese engineers have been pioneering "intelligent" robots for demining for some time (Habib 2008: 42–44).

UAV applications will continue to advance quickly in their sophistication and demining applications, moving from experimental trials to dedicated field tests (senseFly 2016: 5). One of the major academic journals focused on humanitarian demining dedicated an issue to the topic (Risser 2018). Various humanitarian demining groups have evaluated and tested UAV systems under operational conditions (Cruz et al. 2018; Gottwald, Docci, and Mayer, 2017; senseFly 2016; Wade 2016). Some have even developed applications using UAVs themselves for the extraction of mines (Mine Kafon 2019; UAV Systems 2016). As the development of experimental work continues, gradual recognition of UAV technology by the UN Mines Action Service as a viable tool has been seen as well (UNMAS, 2018: 30).

Other R&D possibilities that can be explored are fluorescent bacteria (Meurer et al. 2009) and novel animal-based detectors (e.g., involving a mongoose [Nanayakkara et al. 2008]). While many of today's R&D projects are "blue sky" projects that may never reach the field during the funding cycle, some of them will reach maturity. This gives new hope that technology may yet come to the service of humanitarian demining. Long-term R&D investments can pay real dividends because the landmine and UXO problem remains so serious. Civilian technologies have produced some fruitful detection and foliage clearance devices. Smartphone and common GIS (like Google Earth) have helped in imaging, data analysis, visualization, and precise clearance marking for demining.

But the detection and extraction technologies are slower to come online, seemingly "stuck in the mud." Devices mentioned earlier show promise but need encouragement and multi-year funding. Unfortunately, "[m]any promising technologies have not been exploited due to the lack of available funding. Although funds may exist, there is currently no formal mechanism to link donors to technology opportunities, and vice versa" (UNMAS 2013: sec. 9). To complete the laboratory-to-field R&D cycle, prototype field testing by established deminers is a much-needed validation step, but R&D risks, high and often multi-year financial commitments, and policy constraints pose significant hurdles (ibid. 9). Despite the best efforts of academic and non-governmental organizations, and biennial workshops organized by GICHD, there is still a need for an organization able to test devices independently and publish impartial results, as well as to set proven standards. The *Landmine Monitor* annual reports could consider developments in technology, something it has avoided doing for the last decade (from 2009 through 2018 it made no mention of technology related to demining operations). However, the Croatian Centre for Testing, Development and Training, at its annual International Symposium on Mine Action, does publish specific advances in demining technology R&D in its International Symposium on Mine Action Book of Papers (HCR-CTRO 2019). And while the Ottawa Treaty encourages states parties to share demining technology, especially through the UN,[12] those efforts have petered out in recent years.[13]

Increasingly, advanced database technologies coupled with data collection tools, including sensors on devices — the "Internet of Things" revolution — will enhance the full spectrum of demining efforts, including integrating mapping, data collection, analysis, and modelling. Tools developed specifically for the mine action community have started to make an impact (Vikström and Kallin 2018), with the GICHD Information Management System for Mine Action being used in 47 countries (GICHD 2019). Finally, demining accident records need to be fed into a centralized, open database to derive lessons about safety, to improve industry technologies and practices, and enable detailed research and study.[14]

The need to clean up mines and other ERW will remain far into the foreseeable future, with new mines and IEDs still being planted. Even cleaning up the landmines currently in the ground would take many decades at the current pace, while accidental deaths would continue. R&D into new technologies and better equipment will require iterative development and refinement over the years. The connection from R&D to field application urgently needs to be strengthened. Mine action specialist Andy Smith sums it up: "We need young ideas, young idealism, young enthusiasm — and, of course, some old and hard money".[15]

Notes

1. Locating and deciding to begin demining activities includes socio-economic impact studies to determine areas that are presumed affected by mines and where demining would be most beneficial to the local population, gathering data and information to identify likely minefields, and reviewing accident reports, satellite photographs, etc. (The HALO Trust n.d.). This pre-demining activity, known as "non-technical survey," has been greatly improved by technology, including satellite and airborne surveillance, modern geographical information systems (GIS) such as ArcGIS and services such as Google Earth, although gaps remain (Schmitz et al. 2018). It is then augmented by "technical survey," which includes physically assessing for mines in a defined area. That is "a process using physical intervention that might include machines or breaching by manual deminers" (The HALO Trust n.d.).
2. Mini-flails reduce risks by setting off booby-traps, trip-wires, fused and even simple-pressure mines. Andy Smith (2015b) comments: "Before it was invented, the most common cause of deminer death was the bounding fragmentation mine. A mini-flail can break or initiate these before the deminers have to go near, removing undergrowth and so making the demining process both faster and safer."
3. Andy Smith, Emails to the author, 20–24 May 2015.
4. Andy Smith, an expert mine action specialist, writes: "Variations in ground density give false signals when the ground has wet patches, rocks, tree roots or voids. The density change between ground and air makes it difficult for GPR to reliably

detect small objects in that area. False alarms encourage the user to make spurious assessments; and accidents have occurred when military deminers have trodden on a mine that they had detected but had chosen to ignore because of the GPR" (2015b).

5 Examples of handheld dual-sensor detectors on the market include, e.g., "Groundshark" by Chemring (2019a); the "Minehound" series by Vallon (2019), HSTAMIDS from the US Army (US DoD 2019), and ALIS (Sato 2018).

6 The "maturity" column gives an indication of the time-span until the technology might be incorporated into practical application.

7 These bulk explosive detectors use radioactive sources to bombard the ground with radiation. They require heavy shielding. There is also a risk of losing radioactive sources to terrorist groups in conflict zones who might seek to make a "dirty bomb."

8 Andy Smith, Emails to the author, 20–24 May 2015.

9 The first humanitarian dog programme started in 1989 in Afghanistan/Pakistan (under Op Salam) in conjunction with UN Development Programme and the UN Good Offices Mission in Afghanistan and Pakistan. Norwegian People's Aid (NPA) further pioneered the use of demining dogs in the mid-1990s. After a disappointing and costly programme in Angola, NPA established its Global Training Centre for Mine Detection Dogs in Bosnia in 2004 (NPA-GTC/MCC 2012). The Norwegian Agency for Development Cooperation found that "more than 25 organisations worldwide currently use mine detection animals [dogs]" (Norwegian Agency for Development Cooperation 2009: 42).

10 Andy Smith, Emails to the author, 20–24 May 2015.

11 For instance, the 2008 movie *The Hurt Locker* depicts the remote-controlled tracked TALON USG for the investigation of IEDs.

12 The Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti-Personnel Mines and On Their Destruction Anti-Personnel Mines Treaty (1997), in Article 6, on International Cooperation and Assistance, Paragraph 2: "Each State Party undertakes to facilitate and shall have the right to participate in the fullest possible exchange of equipment, material and scientific and technological information concerning the implementation of this Convention. The States Parties shall not impose undue restrictions on the provision of mine clearance equipment and related technological information for humanitarian purposes." Then in Paragraph 7(b): Each State Party shall provide "the financial, technological and human resources that are required for the implementation of the [mine clearance] program." In Article 11, on Meetings of the States Parties, the signatories commit to "meet regularly in order to consider [...] 1(d) The development of technologies to clear anti-personnel mines."

13 While the International Test and Evaluation Program for Humanitarian Demining, with a secretariat in Brussels, is now closed, an important role continues to be played by the Swiss-based GICHD. Organisations like the Centre for Testing, Development and Training and the Croatian Mine Action Centre are a kind of "halfway house" to test and coordinate humanitarian demining efforts. The Demining Technologies Information Forum (DTIF), launched by Canada, the European Commission and the United States and joined later by UNMAS, GICHD, and a number of nations, once provided a "systematic, multi-disciplinary opportunity for the identification of demining technology gaps, for the synergistic exchange of ideas, for collaborative international programme co-ordination and planning and for the review of progress in the mine action technology area. [...] Regrettably, the DTIF is no longer functioning" (UNMAS

2015). Fortunately, the NGO Find a Better Way continues to work with various UK universities to explore better landmine detection and removal methods (Find a Better Way 2019).

14 A database on deminer injuries is available, although reporting is voluntary and far from complete (Global CWD Repository 2019). Some have argued that the humanitarian demining community ought to recognize a duty of care for its deminers and provide detailed records of incidents globally (Smith 2017a), as others have done in specific former conflict zones (Debač 2016).

15 Andy Smith, Emails to the author, 20–24 May 2015.

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The author has no competing interests to declare.

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